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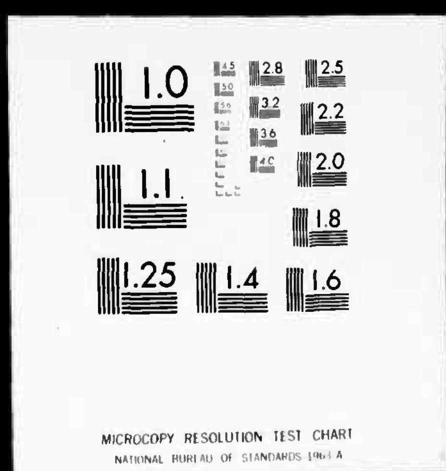
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A Steady State and Dynamic Analysis of a Mooring System

James P. Radochia
Special Projects Department

25 March 1977

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This report investigates the forces acting upon a cable-buoy-ship system and develops a digital computer simulation of its dynamics in three dimensions. The system that is discussed is excited by ship motions caused by ocean waves.

Equilibrium equations are written for the subsurface buoys and cable for the steady state case, in which ship motions are assumed to be zero. A Runge-Kutta scheme is used to solve the cable equations, and an iterative process

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20. Abstract (Cont'd)

cont

is employed to effect the correct solution for the system.

For the dynamic case, in which ship motions do exist, a lumped mass model of the cable and subsurface buoys is used. The equations of motion for each lumped mass element are numerically integrated simultaneously in the time domain. A particular cable-buoy-ship system is investigated, and the results are analyzed.

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Symbols

A Transform matrix from cable coordinates to inertial coordinates

b Integration step-size in time domain for dynamic model

B Net buoyancy of subsurface buoy (buoy displacement minus air weight of buoy; also defined to be excess buoyancy)

c_B Current magnitude at ocean bottom

c_{DN} Normal drag coefficient for cable

c_{DS} Coefficient of drag for spherical subsurface buoy

c_{DT} Tangential drag coefficient for cable

c_x Current magnitude at surface

c_y Current magnitude at depth D

d Outside diameter of the cable

d_S Effective strength member diameter of cable

D Depth of water above which current varies exponentially, and below which it varies linearly

D_F Current drag on subsurface buoy

D_x", D_y", D_z" Cable drag components in cable coordinates

E_A Distance between calculated location and actual location of ship

E_c Modulus of elasticity of cable

f_h Highest natural frequency of system

G Horizontal distance between anchor and ship

Symbols (Cont'd)

H	Water depth
$\hat{i}, \hat{j}, \hat{k}$	Direction indices
Ky^n	Spring constant
Δl_n	Length of n'th segment
$m_{h_x}{}^n$, $m_{h_y}{}^n$, $m_{h_z}{}^n$	Hydrodynamic mass components in cable coordinates
Re	Reynolds number
R_s	Radius of subsurface buoy
s	Stretched length of cable
s_o	Unstretched length of cable
$S_{h_{x_i}}$, $S_{h_{z_i}}$	Constants used to describe ship motions
t	Time
T	Tension vector
T_{AN}	Corrected tension at anchor
T_{BD}	Tension in cable from ship at subsurface buoy
T_{BB}	Tension in cable from anchor at subsurface buoy
Ty^n	Tension in n'th cable segment
u, v, w	Components of ocean currents in inertial coordinates
U_{RN}, V_{RN}, W_{RN}	Resultant velocity components of the water relative to the cable components in inertial coordinates
v_c	Current velocity
w_b	In water weight of subsurface buoy
w_c	In water weight per unit length of cable

Symbols (Cont'd)

x, y, z	Spatial coordinates
$\bar{X}, \bar{Y}, \bar{Z}$	Force components acting on cable
z_{SH}	The calculated "z" coordinate of the ship
δ_A	Positive number which is successively reduced in iteration scheme
ε	Maximum closure error
ε_i	Phase angle
θ	Cable angle in horizontal plane
θ_c	Current angle in horizontal plane
ϕ	Cable angle in vertical plane
ρ_w	Water mass density
μ_m	Cable mass per unit length
ν	Kinematic viscosity of seawater
ω_i	Wave frequency

Subscripts

A	Anchor
D	Point of attachment of cable from ship at subsurface buoy
E	Point of attachment of cable from anchor at subsurface buoy
n	Lumped mass element number
N	Iteration number for procedure used to find tension at anchor

I. INTRODUCTION

This study describes an analysis and simulation of the dynamics of simple moored oceanic buoy systems which are tethered to a surface ship. The effects of the wave induced motion of this vessel, the forces due to the waves and currents on the buoy system, and the weight of the cable and buoy are all included. Because of the nonlinearities of the differential equations used to model the system, numerical techniques are used to effect solutions.

The basic problem this simulation will address is the decoupling of the cable connecting the anchor to the subsurface buoys from the wave induced motion of the ship. This will help alleviate the problem that has caused much concern among researchers and navies throughout the world about possible failures in a moored cable due to the fatigue of the cable caused by the wave excited motions of the tethered ship.

Most analyses of the type undertaken in the present study have dealt with some type of moored buoy configuration. Almost all of these studies did not consider systems in which a ship was present; thus, the wave induced motions were limited to affecting only the surface buoy.

Barber [1] compared three methods for obtaining cable displacements, and then examined what effect these displacements would have in the steady state upon current meters.

His main concern was in obtaining accurate data for closely spaced current meters near the top of the mooring.

Martin [2] developed a computer program to determine the steady state geometry and cable tensions in single-point mooring systems. It was based on an iterative, numerical-integration routine for the cable equations, allowing for elastic cables, drag and weight forces, variation of current speed with depth, instruments supported in the mooring line, and the effects of specific buoy shapes.

Griffin and Radochia [3] derived a program to find the steady state configuration and tension of a very long underwater towed cable. A numerical-integration routine was also used to solve the cable equations, which considered the elasticity of the cable, a constant current profile, drag and weight forces, and a drogue at the end of the cable.

Griffin [4] non-dimensionalized the steady state cable equations for single point mooring systems and solved them for different values of the non-dimensional parameters. He plotted the spatial coordinates of the end point as a function of the dimensionless coefficients for drag, cable weight, excess buoyancy-to-tension ratio, current profile, and buoy geometry so that, for a given set of buoy and cable parameters and specific current profiles, the horizontal and vertical excursions of the buoy could be determined.

Shepard [5] described a dynamic model of a vertical

moored taut cable which was subjected to a low velocity transverse flow and which underwent small harmonic oscillations in the vertical direction at its upper end. Calculations based on this model yielded estimates of the dynamic force-displacement relations at the upper end of the cable.

Griffin [6] investigated the forces acting upon a cable-towed body system and developed a digital computer simulation of its dynamics in a plane. The towed system was excited by ship motions caused by deep-ocean waves. Equations of motion for the towed body were written and reduced to a set of ordinary nonlinear differential equations having nonconstant coefficients. A lumped mass model of the towline was employed and the equations of motion for the cable were numerically integrated simultaneously with the towed body equations of motion in the time domain.

Paquette and Henderson [7] used an analog computer to simulate the dynamics of buoy mooring ropes under conditions typical of the open sea. They solved the set of second-order partial differential equations associated with single-point mooring systems under the action of wind and current forces that were unidirectional and coplanar. The cable was simulated by up to ten straight segments joined at node points where all forces and mass were assumed to be lumped.

Brainard [8] analyzed the dynamic motion of a single point, taut, compound mooring. His model consisted of a

series of discrete masses connected with linear springs; motion was assumed to be one-dimensional along the longitudinal axis of the model. The analysis predicted the natural frequencies of the model without damping. These results were used as a basis for analyzing motion of the masses and tensions in the springs when the model was driven with an external force and where damping, from tangential drag, was assumed to be proportional to velocity squared. Solutions were obtained by computer programmed numerical techniques; both steady state and transient cases were studied. Response of the system with alterations of drag and spring stiffness were also studied.

Patton [9] investigated a digital computer simulation of buoy system dynamics for simple buoy systems, that is, a surface buoy moored on a single mooring line. The buoy system could be excited by winds, waves, and currents. Winds could act from any compass direction, and currents could vary in strength and direction as a function of depth in the water column. Wind waves were simulated by first computing their properties with the Sverdrup-Munk [12] - Bretschneider [13] method and then by using Bargman's [14] energy partitioning scheme on a two-parameter Bretschneider spectrum to compute component sine wave amplitudes, phases, and frequencies.

Equations of motion for the buoy, assumed to be an

oblate spheroid, were developed for six degrees of freedom-three translational and three rotational. Hydrostatic and hydrodynamic forces and moments acting on an oblate spheroid moving on the free surface of an infinite body of water were investigated in detail. The set of integro-differential equations for buoy motions were reduced to a set of nonlinear, ordinary differential equations with nonconstant coefficients by using the Haskind [15] hypothesis to evaluate the hydrodynamic force and moment integrals and to represent them as frequency dependent coefficients. Buoy motions were coupled to the hydrostatic, hydrodynamic, and mooring line forces.

Cable dynamics were also investigated. A set of coupled, hyperbolic, partial differential equations for cable motions were developed and characteristic equations were derived to effect a method of characteristics solution. A unique numerical method of characteristics technique, based upon Hartree's [16] method, was developed for the solution of the cable equations in the time-space domain. Buoy motions, which were dependent upon the cable tensions, served as the upper boundary conditions. Lower boundary conditions were prescribed at the anchor, where there could be no motion.

For certain buoy systems, where many mass discontinuities existed along the cable, or for shallow water moorings,

where slack cable conditions could exist, a lumped mass method of computing cable dynamics was developed as opposed to the finite difference method just described. In general, for cable dynamics the lumped mass numerical method was an order of magnitude faster in computation time than the finite difference method.

The equations of motion developed for the buoy were solved numerically in the time domain using a fourth-order, Runge-Kutta integration method. Cable equations could be solved by finite difference methods or by integrating with the Runge-Kutta algorithm for the lumped mass model.

In order to validate the numerical models developed, two buoy systems were instrumented and deployed in Block Island Sound. The motion data from these experiments, along with data published in the literature (10, 11), were compared with simulated buoy motion data. This comparison (9) indicated that steady state buoy system forces and configurations could be predicted within approximately five percent and that buoy system dynamics could be predicted within approximately fifty percent. There were some indications that the surge and sway hydrodynamic forces acting on the buoy were being underestimated by the computer model.

Webster (17) tested models of three buoys; in these tests, the effects of both waves and currents were simulated. As a result of the tests, a single-point mooring configura-

tion for a new buoy was developed. Of particular interest during this study was the visibility of the buoys in various sea and current conditions. The test results were used to predict the fraction of time that the buoys remained within two, three, and four degrees of the vertical.

Mercier [18] presented the results of hydrodynamic tests of several models of typical buoy shapes. Measurements of lift, drag, and pitch moment were made for the heave, surge, and pitch modes of motion in calm water and for the model held fixed with surface waves passing by. These results were necessary for evaluating the motions of these bodies for arbitrary mass distributions, using the equations of motion. Coefficients expressing the inertial and damping characteristics of these models, based on the assumption of linearity of forces with motion and wave amplitude were presented in tables. Amplitudes and phases for the wave exciting forces were tabulated. Models that had been tested included a half-immersed sphere, a half-immersed torus, a one-fiftieth scale model of the "Monster Buoy", a shallow draft rectangular barge, and a cylinder with a square damping plate at the lower end and with a hemispherical bottom cap.

The problem considered by Reid [19] dealt with the motions of and tensions within a quasi-elastic mooring line which was anchored at the sea floor while attached to a ship

er buoy at or near the sea surface and subject to the influence of time varying currents. This was a natural extension of previous studies, such as those of Wilson,[20, 21] dealing with the equilibrium configuration of an anchored cable in the presence of steady, coplanar currents.

The design concept and a summary of the motion analysis of the mathematical model of a tri-moored buoyant structure were presented by Savage [22] for project SEASPIDER. The need to adapt the structural design to the anticipated oceanographic environment in order to obtain a near-motionless system was discussed. Critical components of the total system were discussed, and experience with these components during sea trials was recorded. Sea trials of the system conducted on the Blake Plateau in 2600 feet of water were reviewed and the results using the system as a base for acoustic, temperature, and current measurements were presented. Evidence of the near-motionless characteristics of this tri-moored buoyant structure was presented and discussed. The purpose of project SEASPIDER had been to prove the feasibility of tri-moored buoyant structures with neutrally buoyant legs as instrument bases for all types of oceanographic measurements in the water column of the deepest parts of the ocean.

Correll [23] reported the results of an analytical design study and a prototype experimental program which inves-

tigated the characteristics and performance of a buoy system for the U.S. Naval Oceanographic Hysurch Program. The buoy system served as a reference station for a hyperbolic navigation system for coastal hydrographic survey. The work consisted of an analytical evaluation of several classes of buoy systems, a detailed design of a prototype buoy system, an experimental program with a full scale prototype buoy system in two oceanic environments, and an evaluation of the operational characteristics of the prototype system. The prototype evaluation showed that a highly compliant taut-wire moored surface buoy configuration could provide vertical stabilities of less than eight degrees variation and a watch circle of approximately ten percent of depth, in sea conditions of up to sea state four and with ocean currents up to three quarters of a knot.

Most analyses of the type undertaken in the studies described above have dealt simply with moored buoy-cable systems. The present study will include the dynamic effects of a ship which is tethered to the system as an extension of previous works. In addition to this excitation of the system due to the response of the ship to ocean waves, the other forces which will be considered include water drag (normal and tangential), cable tension, cable and buoy weight, and inertial forces. These will be assumed to be acting at discrete points along the cable in a lumped mass-

spring model. In order to provide initial conditions for this dynamic case, a steady state model will first be developed.

II. STEADY STATE MODEL

2.1 Cable Equations of Motion

The equilibrium equations, originally given by Patton[9], were modified by Griffin and Radochia[3] and used to model extremely long towed arrays. The differential equations generated to describe the equilibrium condition for an element of cable subject to weight and steady hydrodynamic forces are given as:

$$\frac{d\theta}{ds_0} = \left(\frac{1}{T\cos\phi}\right)\left(\frac{1}{2}\rho_w d\, C_{DN}\, u''|u''|\right) \tag{1a}$$

$$\frac{dT}{ds_0} = w_c \sin\phi - \frac{1}{2}\rho_w \pi d\, C_{DT}\, v''|v''| \tag{1b}$$

$$\frac{d\phi}{ds_0} = \left(\frac{1}{T}\right)\left(w_c \cos\phi - \frac{1}{2}\rho_w d\, C_{DN}\, w''|w''|\right) \tag{1c}$$

$$\frac{ds}{ds_0} = 1 + \frac{4T}{\pi d_s^2 E_c} \tag{1d}$$

Equations (1a) through (1c) are the equilibrium equations for the cable in the x", y", and z" directions respectively.

(See figures 2 through 6.) Equation (1d) is derived by using Hooke's law [22] (strain=stress/modulus of elasticity), which is valid for linear elastic materials. (Strain, $\left(\frac{ds}{ds_1} - 1\right)$, is assumed to be very small, and temperature effects on the strain are neglected.) All of the above are for cables with circular cross section.

The parameters used in equation (1) are defined as follows:

$$C_{DN} = \frac{\text{normal drag along } x'' \text{ axis/unit length}}{\left(\frac{1}{2}\right)(\rho_w)(d)(u'')^2}$$

$$C_{DN} = \frac{\text{normal drag along } z'' \text{ axis/unit length}}{\left(\frac{1}{2}\right)(\rho_w)(d)(w'')^2}$$

C_{DN} = the normal drag coefficient of the element along the x" axis and z" axis

$$C_{DT} = \frac{\text{tangential drag/unit length}}{\left(\frac{1}{2}\right)(\rho_w)(\pi)(d)(v'')^2}$$

C_{DT} = the tangential drag coefficient of the element along the y" axis

d = the outside diameter of the element (see figure 1)

d_e = the effective strength member diameter (see figure 1)

E_e = the modulus of elasticity of the effective strength member

s = the stretched length of the element

s_o = the unstretched length of the element

T = the tension at the element

w_c = the in water weight per unit length of the cable element (For the cable, weight is defined as a positive quantity; the equilibrium equations of the cable take into account the fact that the positive weight is acting in the negative z direction.)

u'', v'', w'', = the fluid velocity components in the double primed coordinate system along the x'', y'', and z'' axes respectively (See figures 2 through 4.)

ρ_w = the mass density of sea water

θ, ϕ = the angles of the cable in the double primed coordinate system, defined in figures 2 through 4.

Equation (1) uses two different values for the cable diameter. The first, d, is the outside diameter; the second, d_s, is the strength member diameter. A cable may sometimes have a buoyancy material, such as thermoplastic rubber, extruded over the load bearing member (see figure 1). This will have little effect upon the stress-strain relations of the cable, but will affect the drag forces on the cable. This fact is taken into consideration when deriving equation (1).

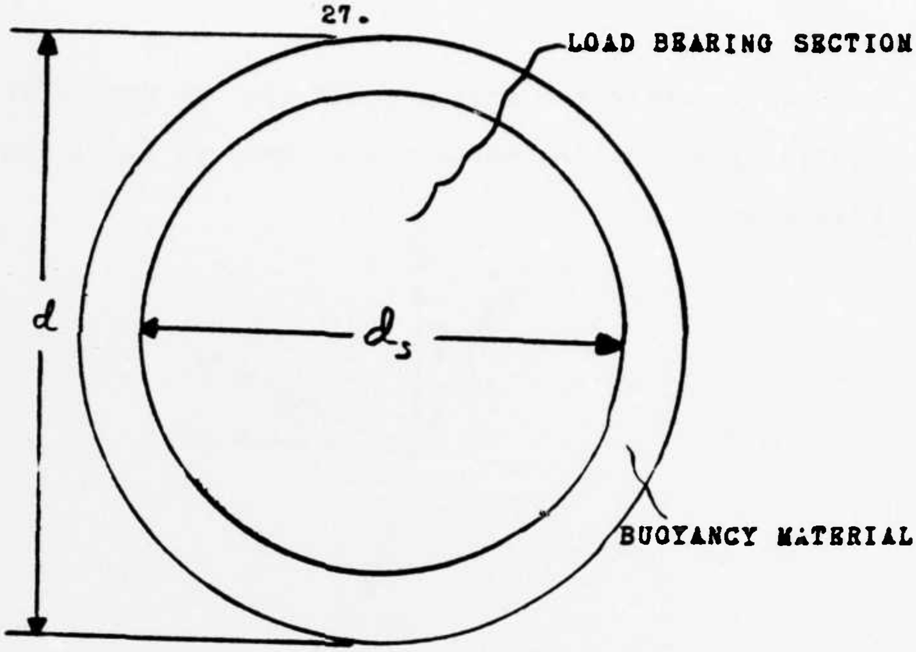

Figure 1. Cable Diameters

To transform from inertial (unprimed) to cable (double primed) coordinates, first rotate the x-z plane about the z axis as shown in figure 2:

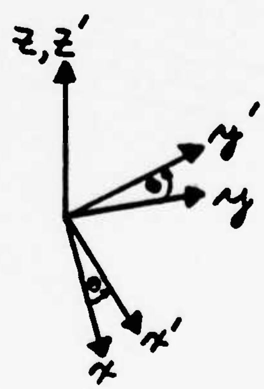

Figure 2. Rotation from Unprimed to Primed System

Next rotate the primed system to the double primed system by a rotation about the x' axis as shown below in figure 3:

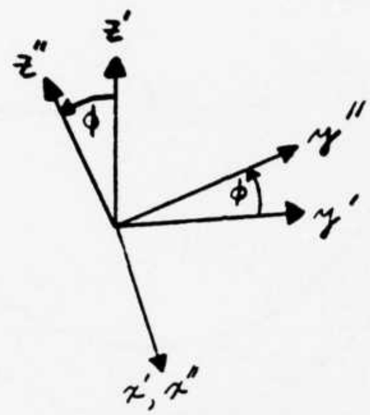

Figure 3. Rotation from Primed to Double Primed System

The cable element is aligned with the y" axis in the double primed coordinate system as shown in figure 4:

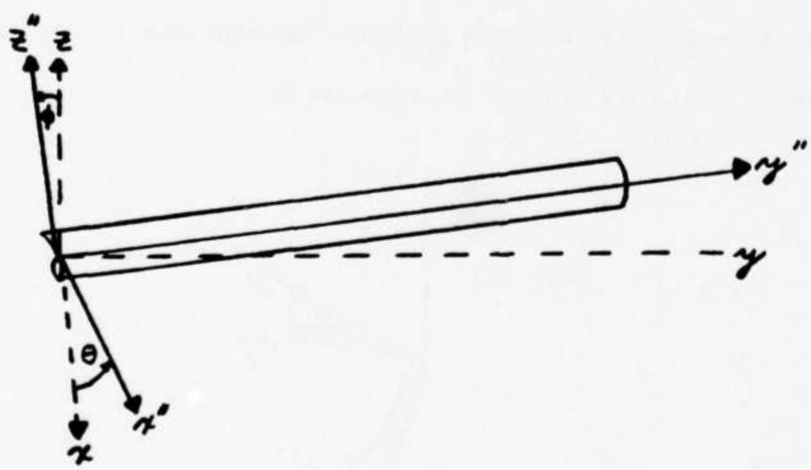

Figure 4. Cable Element in Inertial and Cable Coordinates

The changes in the horizontal angle θ and the vertical angle ϕ in the inertial system are shown below in figures 5 and 6:

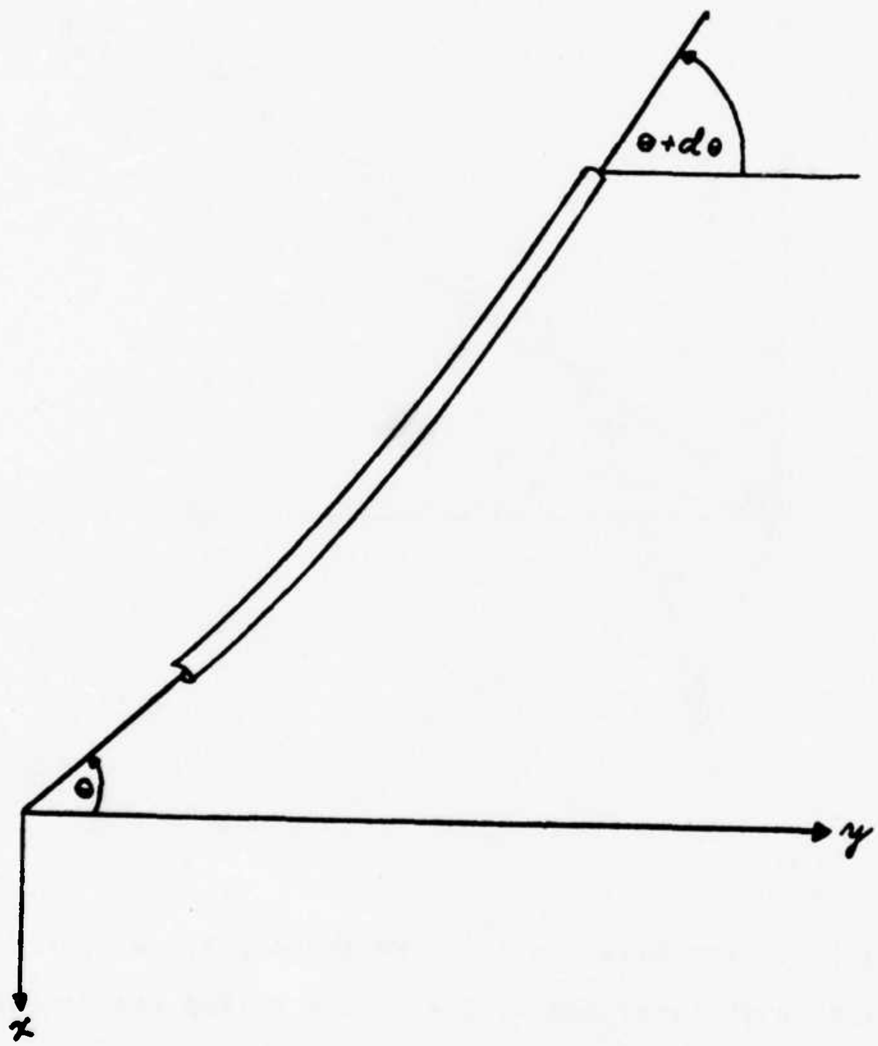

Figure 5. Horizontal Angle Change

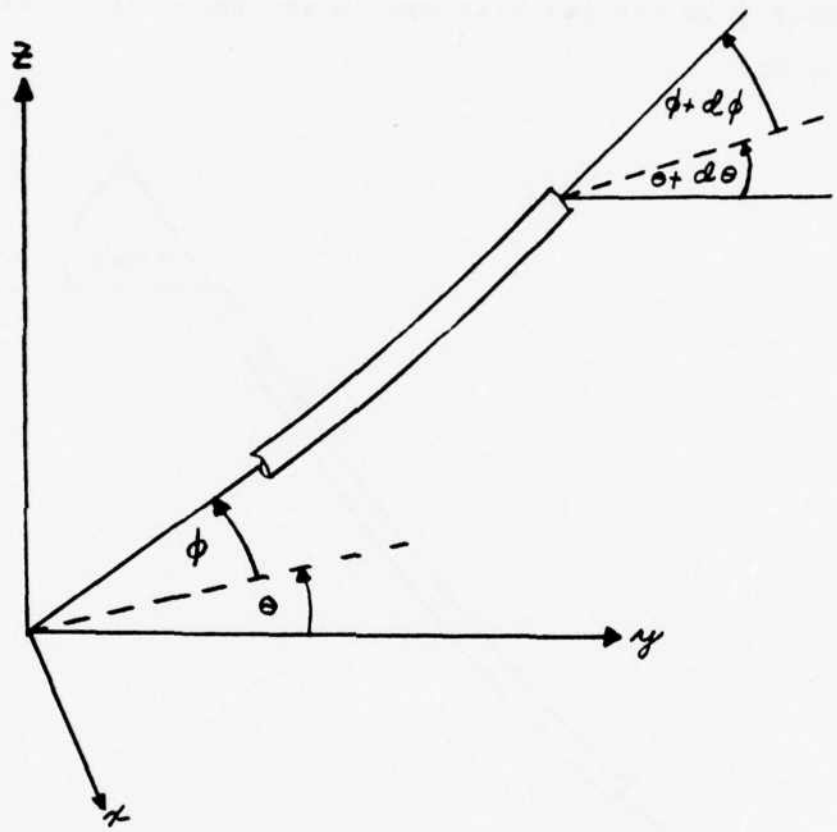

Figure 6. Vertical Angle Change

Griffin and Radechia [3] give the transform matrix to change from the unprimed to the double primed coordinate system as:

$$A = \begin{bmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta\cos\phi & \cos\theta\cos\phi & \sin\phi \\ \sin\theta\sin\phi & -\cos\theta\sin\phi & \cos\phi \end{bmatrix} \qquad (2)$$

Its inverse is given as:

$$A^{-1} = \begin{bmatrix} \cos\theta & -\sin\theta\cos\phi & \sin\theta\sin\phi \\ \sin\theta & \cos\theta\cos\phi & -\cos\theta\sin\phi \\ 0 & \sin\phi & \cos\phi \end{bmatrix} \quad (3)$$

Using the above relations u", v", and w" may be defined as the fluid velocity components in the x", y", and z" directions respectively:

$$u'' = u\cos\theta + v\sin\theta \quad (4a)$$

$$v'' = -u\sin\theta\cos\phi + v\cos\theta\cos\phi + w\sin\phi \quad (4b)$$

$$w'' = u\sin\theta\sin\phi - v\cos\theta\sin\phi + w\cos\phi \quad (4c)$$

where u, v, and w are the current components in the x, y, and z directions respectively (the inertial coordinate system). Note that u", v", and w" may be a function of depth, if desired.

Equations (1) are numerically integrated using a fourth order Runga-Kutta method[25]. A brief description of this method is presented in Appendix A; further details may be found in Kelly [26] or Nielsen [27].

The following inertial coordinates of the element are computed once a solution for T, θ, and ϕ is obtained for each element of cable, ds. (It is assumed in this study that the unstretched length of ds is 20 feet.)

$$dx = - ds \sin\theta \cos\phi \tag{5a}$$

$$dy = ds \cos\theta \cos\phi \tag{5b}$$

$$dz = ds \sin\phi \tag{5c}$$

The Runge-Kutta method used in this simulation has been checked for accurate performance by White [25] for many representative differential equations. The intent was to provide a subroutine which performed the "dirty work" and required the programmer only to write expressions for the derivatives involved in his particular differential equations. For the present study, this formulation was found to provide sufficient accuracy with rapid convergence.

2.2 Subsurface Buoy Equations

2.2.1 Force Equilibrium Equations

As discussed in the previous section, a numerical integration procedure is used to solve the cable equations. At a buoy, however, this scheme must be interrupted, and

the force and moment equilibrium equations for the buoy must be solved in order for the integration to proceed at the next cable element on the "other side" of the buoy.

A free body diagram of the subsurface buoy, which is assumed to be spherical in shape, is shown below:

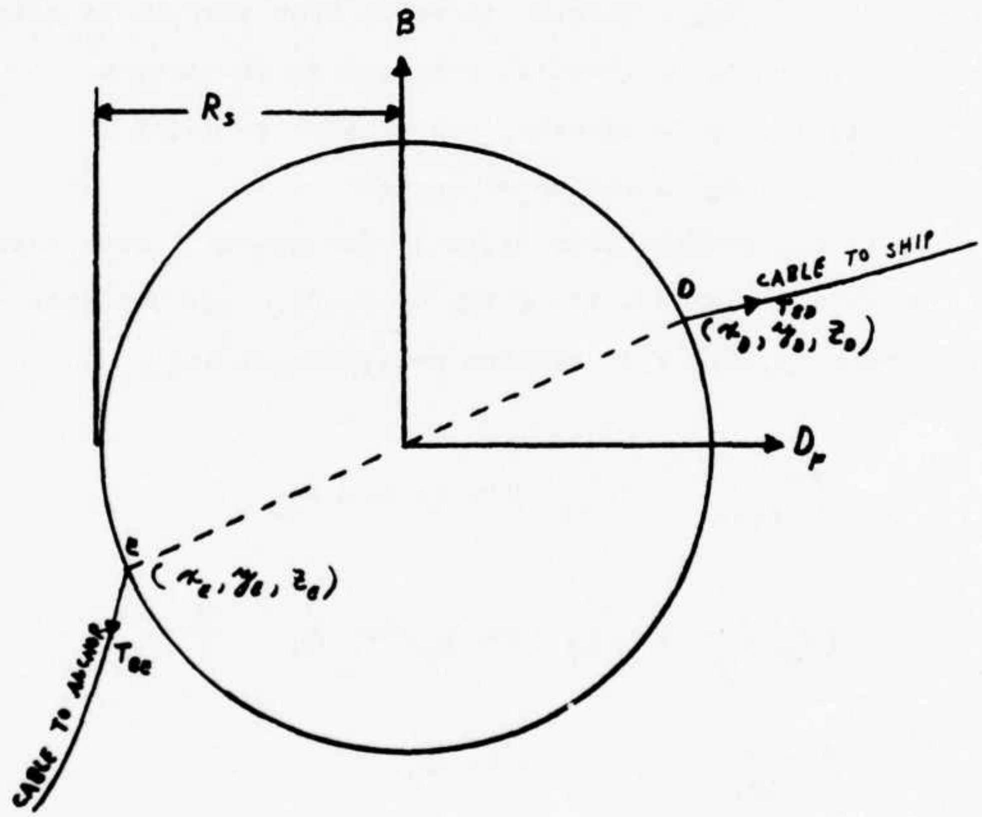

Figure 7. Free Body Diagram of Subsurface Buoy

where

B = net buoyancy of buoy (buoy displacement minus air weight of buoy)

D_E = drag (assumed to be in the horizontal plane, ie., no vertical currents exist)

T_{BE} = tension on cable from anchor at point E

T_{BD} = tension on cable from surface at point D

x_D, y_D, z_D = inertial coordinates of point D

x_E, y_E, z_E = inertial coordinates of point E

R_s = radius of sphere

The tension components in the inertial coordinate system at point E are given by Griffin and Radochia [3] in the x, y, and z directions respectively as:

$$(T_{BE})_x = -T_{BE} \sin\theta_{BE} \cos\phi_{BE} \tag{6a}$$

$$(T_{BE})_y = T_{BE} \cos\theta_{BE} \cos\phi_{BE} \tag{6b}$$

$$(T_{BE})_z = T_{BE} \sin\phi_{BE} \tag{6c}$$

where θ_{BE} and ϕ_{BE} are the horizontal and vertical angles respectively of the cable at point E described earlier in figures 2 through 6. These are considered to be measured positive counterclockwise from the y axis and positive

upwards from the x-y plane respectively. (This will be true whenever the symbols θ and ϕ are used at any point.) The tension magnitude T_{BE} and the angles θ_{BE} and ϕ_{BE} are already known from the solution of the cable equations at point E.

The tension components at point D may be given by:

$$\left(T_{BD}\right)_x = -T_{BD} \sin \theta_{BD} \cos \phi_{BD} \tag{7a}$$

$$\left(T_{BD}\right)_y = T_{BD} \cos \theta_{BD} \cos \phi_{BD} \tag{7b}$$

$$\left(T_{BD}\right)_z = T_{BD} \sin \phi_{BD} \tag{7c}$$

where θ_{BD} and ϕ_{BD} are the horizontal and vertical angles respectively of the cable at point D. The tension magnitude T_{BD} and the angles θ_{BD} and ϕ_{BD} are three of the unknowns in this problem.

The buoyancy force, B, will always be acting vertically upwards; thus, its only component is in the z direction.

The drag, D_F, will be assumed to be acting in the horizontal plane. This is a consequence of the assumption

that the current velocity vector at any depth is contained in a horizontal plane, that is, $w = \phi = 0$. Furthermore, the current velocity attenuation with depth is insignificant and can be assumed to be non-existent across the sphere. Thus, the current magnitude is given as v_c and its direction as θ_c, where θ_c is measured positive counterclockwise from the inertial y axis. Berteaux [28] gives the drag force as:

$$D_F = \frac{1}{2} \rho_w C_D A v_c^2 \tag{8}$$

where ρ_w = mass density of sea water

c_D = coefficient of drag for the buoy

A = projected area of the buoy in the vertical plane

For a sphere,

$$A = \pi R_s^2 \tag{9}$$

Thus, the components of drag for the subsurface buoy are given as:

$$(D_F)_x = \frac{1}{2} \rho_w c_{Ds} (\pi R_s^2)(-v_c \sin\theta_c)(|-v_c \sin\theta_c|) \tag{10a}$$

$$(D_F)_y = \frac{1}{2} \rho_w c_{Ds} (\pi R_s^2)(v_c \cos\theta_c)(|v_c \cos\theta_c|) \tag{10b}$$

where c_{DS} is the coefficient of drag for a sphere at Reynolds Number Re, where Re is a function of the current velocity, buoy diameter, and the kinematic viscosity of seawater (ν) as follows:

$$R_e = \frac{2 v_c R_s}{\nu} \tag{11}$$

Using the above expressions for the cable tension, drag, and gravitational force, three force equilibrium equations may be written to solve for the three unknown tension components. They are written, for the x, y, and z directions respectively, as:

$$-(T_{BE})_x + (D_F)_x - (T_{BD})(\sin\theta_{BD})(\cos\phi_{BD}) = 0 \tag{12a}$$

$$-(T_{BE})_y + (D_F)_y + (T_{BD})(\cos\theta_{BD})(\cos\phi_{BD}) = 0 \tag{12b}$$

$$-(T_{BE})_z + (B) + (T_{BD})(\sin\phi_{BD}) = 0 \tag{12c}$$

These equations are solved in Appendix B.1; their solution, from equations (B9), (B12), and (B13) in Appendix B, is as

follows:

$$\theta_{BD} = \tan^{-1}\left[\frac{AEX}{AEY}\right] \tag{13a}$$

$$\phi_{BD} = \tan^{-1}\left[\left(\frac{AEZ}{AEY}\right)\left(\cos\theta_{BD}\right)\right] \tag{13b}$$

$$T_{BD} = \left[\frac{AEZ}{\sin\phi_{BD}}\right] \tag{13c}$$

where

$$AEX = \left[-(T_{BE})_x + (D_F)_x\right] \tag{14a}$$

$$AEY = \left[(T_{BE})_y - (D_F)_y\right] \tag{14b}$$

$$AEZ = \left[(T_{BE})_z - (B)\right] \tag{14c}$$

2.2.2 Moment Equilibrium Equations

The moment equilibrium equations may be developed as follows. Let

$$x_{DE} = x_D - x_E \,, \tag{15a}$$

$$y_{DE} = y_D - y_E \,, \quad \text{and} \tag{15b}$$

$$z_{DE} = z_D - z_E \,. \tag{15c}$$

Then, the moments about point E may be written as:

$$(B)\left(\frac{y_{DE}}{2}\right) + (T_{ED})_z (y_{DE}) - (D_F)_y \left(\frac{z_{DE}}{2}\right) - (T_{ED})_y (z_{DE}) = 0 \tag{16a}$$

$$(D_F)_x \left(\frac{z_{DE}}{2}\right) + (T_{ED})_x (z_{DE}) - (B)\left(\frac{x_{DE}}{2}\right) - (T_{ED})_z (x_{DE}) = 0 \tag{16b}$$

$$(D_F)_y \left(\frac{x_{DE}}{2}\right) + (T_{ED})_y (x_{DE}) - (D_F)_x \left(\frac{y_{DE}}{2}\right) - (T_{ED})_x (y_{DE}) = 0 \tag{16c}$$

Since all the forces considered in the problem cut line $\overline{ED}$, equations (16) reduce from three to only two independent equations. A third independent equation, which states that line $\overline{ED}$ passes through the center of the sphere, may be written from the physical geometry of the buoy:

$$(2R_S)^2 = (x_{DB})^2 + (y_{DB})^2 + (z_{DB})^2 \quad (17)$$

Their solution is given in Appendix B.2, where equations (16a), (16b), and (17) have been used as the three independent equations. From equations (B-21), the coordinates of point D are given as:

$$x_D = x_E + x_{DB} \quad (18a)$$

$$y_D = y_E + y_{DB} \quad (18b)$$

$$z_D = z_E + z_{DB} \quad (18c)$$

where, from equations (B20), (B19a), and (B19b):

$$z_{DB} = \frac{D_S}{\sqrt{\left(\frac{c_2}{c_1}\right)^2 + \left(\frac{c_3}{c_1}\right)^2 + 1}} \quad (19a)$$

$$y_{DB} = \left(\frac{c_2}{c_1}\right)\left(z_{DB}\right) \quad (19b)$$

$$x_{DB} = \left(\frac{c_3}{c_1}\right)\left(z_{DB}\right) \quad (19c)$$

The constants in the above expressions are defined from equations (B17) as follows:

$$C_1 = \left[\left(\frac{B}{2}\right) + (T_{BD})_z\right] \qquad (20a)$$

$$C_2 = \left[\frac{(D_F)_y}{2} + (T_{BD})_y\right] \qquad (20b)$$

$$C_3 = \left[\frac{(D_F)_x}{2} + (T_{BD})_x\right] \qquad (20c)$$

$$D_S = (2)(R_S)$$

2.3 Iterative Solution for Finding Tension at Anchor

In order to start the integration of the cable equations, the boundary conditions at the anchor must be known. Since the tension and angles at the anchor depend on the final equilibrium configuration, an iterative technique is developed modifying the methods first described by Dominguez and Filmer [29] (which are based on Skop and O'Hara's [30] method of imaginary reactions) and later used by Griffin and Swope [31].

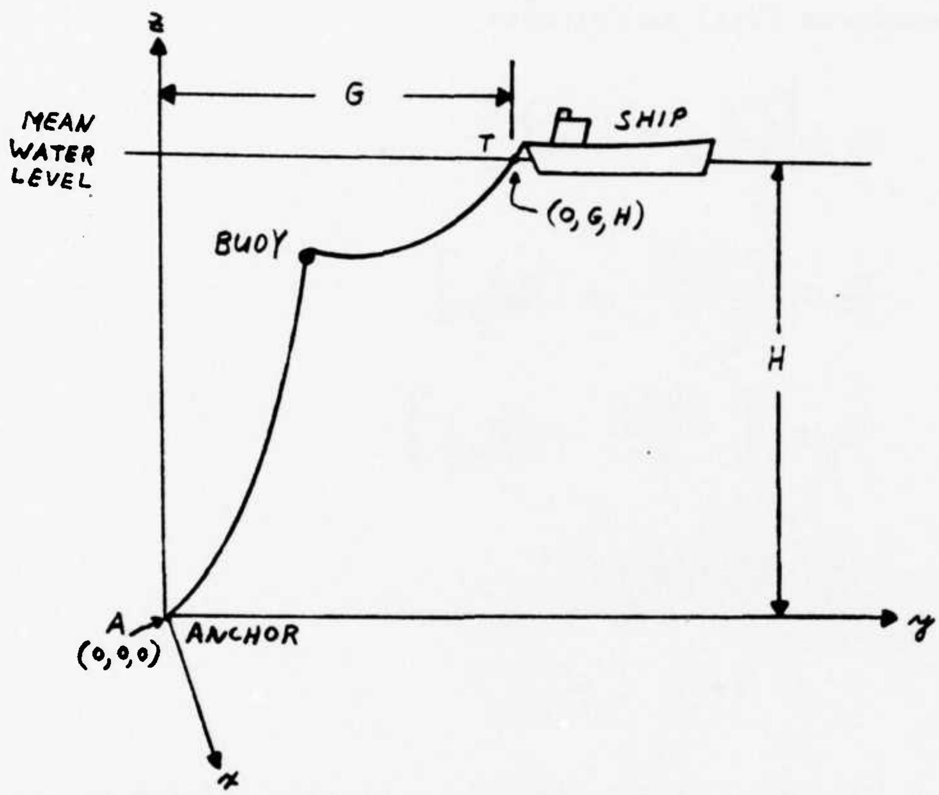

Figure 8. Inertial Coordinate System

It is seen from figure 8 that the anchor is located at $x = 0$, $y = 0$, and $z = 0$. The y axis is the horizontal projection of a straight line taken between the anchor and the first point of submergence into the water of the tether cable from the ship. The z axis is the vertical direction, and, of course, the x axis completes the right handed coordinate system. The first point of submergence into the water of the tether cable from the ship, T, is located at

$x = o$ (due to the alignment of the y axis), $y = G$ (this will be specified), and $z = H$ (the water depth).

The procedure begins by assuming the tension vector at the anchor, $\vec{T_A}$, which includes a magnitude T_A and the two angles θ_A and ϕ_A . (The weight of the anchor is considered to be sufficient to prevent any movement of the anchor; that is, the anchor is assumed to be fixed.) Integration then takes place over the cable up to the first subsurface buoy (if there is one). Equilibrium requirements are satisfied here (see equations 12), and the integration continues along the cable up to the second subsurface buoy (if there is one). After equilibrium requirements again are satisfied, the integration proceeds along the tether to the ship. At the ship, the calculated values for the position of the ship are compared to the specified location of the ship on the surface. (The water depth is known and the position of the ship is specified relative to the anchor due to operational considerations.) These errors are then used in "correcting" the tension at the anchor. The process is repeated until the error reaches a suitably small value. (For the present study, a closure error of ten feet was used at the ship.) This process is described in detail as follows:

$$\Delta x_A = \frac{\delta_A}{\sqrt{E_A}}(O - x_A) \qquad (21a)$$

$$\Delta y_A = \frac{\delta_A}{\sqrt{E_A}}(G - y_A) \qquad (21b)$$

$$\Delta z_A = \frac{\delta_A}{\sqrt{E_A}}(H - z_A) \qquad (21c)$$

where x_A, y_A, and z_A are the calculated values for the position of the ship, and

$$E_A = (O - x_A)^2 + (G - y_A)^2 + (H - z_A)^2 \qquad (22)$$

Let δ_A be some positive number which is reduced at certain iterations so that each iteration produces a smaller closure error, until the value of E_A is less than some prespecified value ϵ. Initially, the value of δ_A is taken to be equal to 3000 if there are no buoys in the system, the excess buoyancy of the buoy if there is one buoy, and the sum of the excess buoyancies of the buoys if there are two buoys. E_A is initially assumed to be ten times the initial value of δ_A. One can choose to reduce δ_A by a factor of two. (Convergence for this method has been indicated by

Dominguez and Filmer [29] and Griffin and Swope [31].)

The tension at the anchor is corrected as follows: Let the new tension be given by

$$T_{AN} = \sqrt{(T_{AN})_x^2 + (T_{AN})_y^2 + (T_{AN})_z^2} \tag{23}$$

where

$$(T_{AN})_x = (T_A)_x + \Delta x_A \tag{24a}$$

$$(T_{AN})_y = (T_A)_y + \Delta y_A \tag{24b}$$

$$(T_{AN})_z = (T_A)_z + \Delta z_A \tag{24c}$$

and, using equation (6),

$$(T_A)_x = -(T_A)(\sin\theta_A)(\cos\phi_A) \tag{25a}$$

$$(T_A)_y = (T_A)(\cos\theta_A)(\cos\phi_A) \tag{25b}$$

$$(T_A)_z = (T_A)(\sin\phi_A) \tag{25c}$$

$\overrightarrow{T_{AN}}$ may be broken up into a magnitude and two angles as follows:

$$T_{AN} = \sqrt{(T_{AN})_x^2 + (T_{AN})_y^2 + (T_{AN})_z^2} \tag{26a}$$

$$\phi_{AN} = \tan^{-1}\left[\frac{(T_{AN})_z}{\sqrt{(T_{AN})_x^2 + (T_{AN})_y^2}}\right] \tag{26b}$$

$$\theta_{AN} = \tan^{-1}\left[\frac{-(T_{AN})_x}{(T_{AN})_y}\right] \tag{26c}$$

where T_{AN}, ϕ_{AN}, and θ_{AN} are the "improved" tension and angles.

At the N'th iteration, E_{A_N} is compared with $E_{A_{N-1}}$. If $E_{A_{N-1}} < E_{A_N}$ the value of δ_A is reduced (by half here), and $\overrightarrow{T_N}$ is computed from $\overrightarrow{T_{N-1}}$ using the new value of δ_A.

The above process was the sole criterion for Dominguez and Filmer [29] and Griffin and Swepe [31] for the reduction of δ_A. It was decided, however, that if a larger error could be predicted in advance, then convergence would be faster. The basic idea of this is to prevent an "over-correction" of the tension at the anchor; that is, if the N'th iteration produced an error significantly smaller than the (N-1)'th iteration, then δ_A should be reduced on the N'th

iteration. Otherwise, too large a correction would be applied at the anchor, resulting in a larger error on the (N+1)'th iteration than on the N'th iteration. This is accomplished by using the following scheme: Let

$$ERRR = \frac{(E_A)_{N-1}}{(E_A)_N} \tag{27}$$

where $(E_A)_{N-1}$ and $(E_A)_N$ are the errors of the (N-1)'th and N'th iterations respectively. If ERRR is greater than two, then δ_A will be reduced in the following manner:

$$(\delta_A)_N = \left(\frac{1}{2}\right)(\delta_A)_{N-1} \tag{28}$$

and $\overrightarrow{T_{AN}}$ is recomputed using $\overrightarrow{T_{A_{N-1}}}$ and the new value of δ_{A_N}. One problem was encountered, however, using this second method: δ_A was sometimes reduced too quickly so that the error was unable to reach a suitably small value. (δ_A was reduced too much, resulting in the tension corrections (Δx, Δy, and Δz of equation (21)) becoming too small.) Thus, while the first method for reducing δ_A is implemented always, this second process is used only when the error is greater than 500 feet; that is, when the ship is calculated to be more than 500 feet from its specified location.

III. DYNAMIC MODEL

3.1 Cable Equations of Motion for a Lumped-Mass System

Many methods are available for analyzing the motions of a cable. The cable may be regarded as a continuum, a series of finite segments, or a series of lumped-mass (concentrated) elements. Both the finite element method and the methods that assume the cable to be continuous are numerical techniques that usually require a great amount of computer time. The lumped-mass method employed in this study to analyze the unsteady motions of a cable is Patton's[9], who states that "a lumped mass analysis can offer significant savings in computational time at the expense of simulation accuracy. In general, the lumped-mass analysis will truncate the high-frequency response of the system. However, for many engineering applications, the high-frequency, low-amplitude response is not of interest, and the cable can be represented as a small number of lumped masses." A similar approach was also taken by Griffin [6] in his model of a cable towed-body system.

The lumped mass models of Patton [9] and Griffin [6] assume that a uniform cable of length L can be broken up into n unstretched segments of length ΔL_n. Figures 9, 10, and 11 show these models for the no buoy, one buoy, and two buoy systems respectively used in this study.

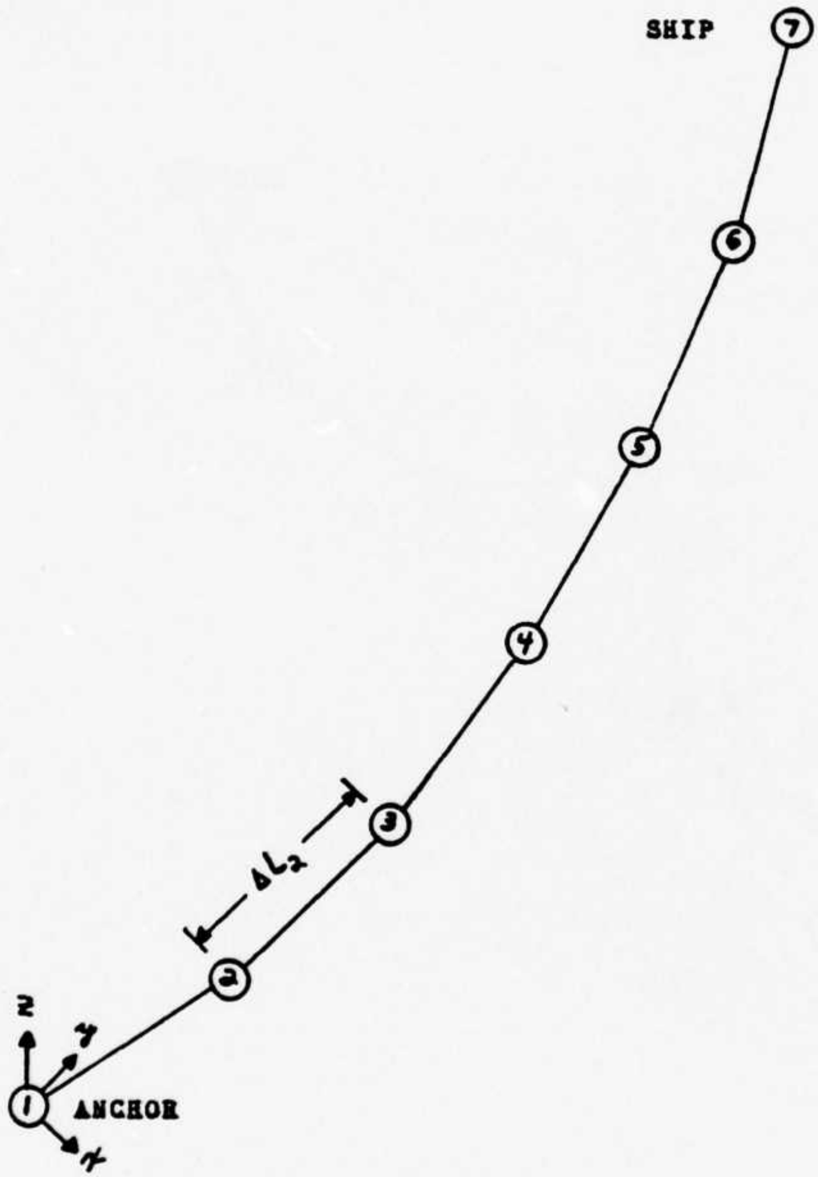

Figure 9. Lumped-Mass Cable Elements With No Buoys

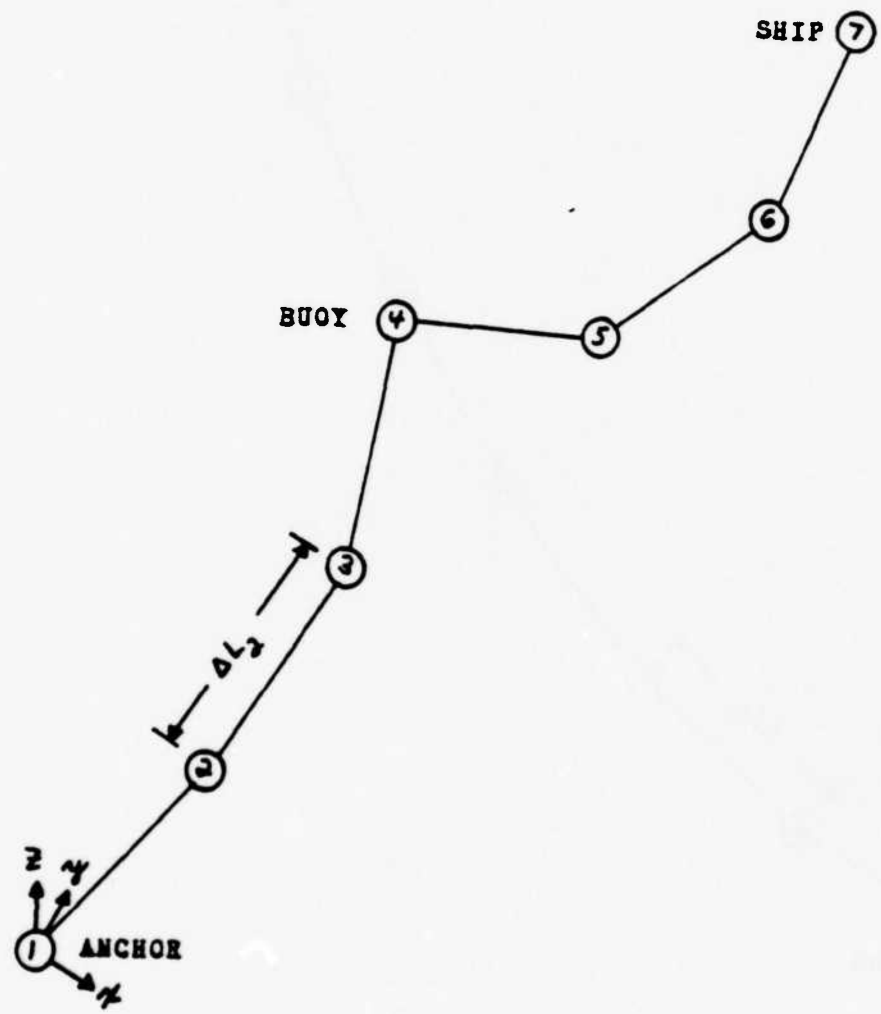

Figure 10. Lumped-Mass Cable Elements With One Buoy

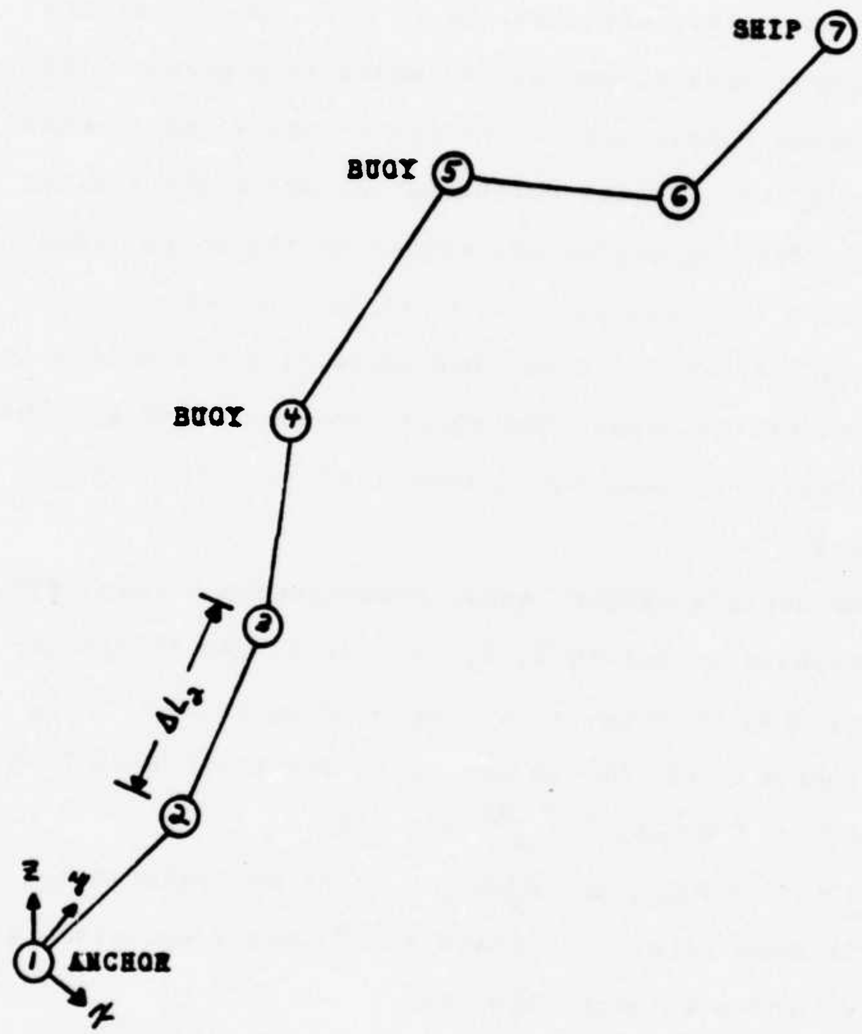

Figure 11. Lumped-Mass Cable Elements With Two Buoys

For the purposes of this study, the system is assumed to be divided up into six segments (m = 6), which results in seven lumped mass elements. As shown in figures 9, 10, and 11, element number one is the anchor and element number 7 is the ship. The forces acting on the cable are assumed to have no effect on either the anchor or the ship. That is, the anchor has neither accelerations nor velocities, and the ship has accelerations and velocities due solely to its wave induced motions. (The ship's motions, when attached to the system, are taken to be identical to those when it is unattached.)

If the cable's weight, mass, hydrodynamic forces, etc., are concentrated at points 2, 3, ..., 5, 6, (which are located ΔL_1, $\Delta L_1 + \Delta L_2$, ..., $\Delta L_1 + \Delta L_2 + \ldots + \Delta L_5$ from the anchor), all forces acting on the cable span from $(\Delta L_1 + \Delta L_2 + \ldots + \Delta L_{n-2} + \frac{\Delta L_{n-1}}{2})$ to $(\Delta L_1 + \Delta L_2 + \ldots + \Delta L_{n-1} + \frac{\Delta L_n}{2})$ will be concentrated at the n'th mass point. Cristecu's (32) cable equations are written for the n'th mass point as:

$$\left(\frac{\mu_n(s_0)\Delta L_n}{2} + \frac{\mu_{n-1}(s_0)\Delta L_{n-1}}{2}\right)\frac{d^2x_n}{dt^2} =$$

$$\left(\frac{\overline{X}_n\,\Delta L_n}{2} + \frac{\overline{X}_{n-1}\,\Delta L_{n-1}}{2}\right) + \left(\vec{T}_n\cdot\hat{i} - \vec{T}_{n-1}\cdot\hat{i}\right) \qquad (29a)$$

$$\left(\frac{\mu_n(s_0)\Delta L_n}{2} + \frac{\mu_{n-1}(s_0)\Delta L_{n-1}}{2}\right)\frac{d^2y_n}{dt^2} =$$

$$\left(\frac{\overline{Y}_n\,\Delta L_n}{2} + \frac{\overline{Y}_{n-1}\,\Delta L_{n-1}}{2}\right) + \left(\vec{T}_n\cdot\hat{j} - \vec{T}_{n-1}\cdot\hat{j}\right) \qquad (29b)$$

$$\left(\frac{\mu_n(s_0)\Delta L_n}{2} + \frac{\mu_{n-1}(s_0)\Delta L_{n-1}}{2}\right)\frac{d^2z}{dt^2} =$$

$$\left(\frac{\overline{Z}_n\,\Delta L_n}{2} + \frac{\overline{Z}_{n-1}\,\Delta L_{n-1}}{2}\right) + \left(\vec{T}_n\cdot\hat{k} - \vec{T}_{n-1}\cdot\hat{k}\right) \qquad (29c)$$

where

$\mu_n(s_o)$ = the mass (structural) per unit length of the n'th cable segment

x_n, y_n, z_n = the inertial coordinates of the n'th mass point

t = time

$\bar{X}_n, \bar{Y}_n, \bar{Z}_n$ = the force components (weight, drag, and added mass forces) per unit length of the n'th cable segment

$\vec{T}_n$ = the cable tension vector of the n'th cable segment

$\hat{i}, \hat{j}, \hat{k}$ = unit vector components

To compute forces acting on each mass element, the cable angles θ and ϕ for each element must be defined. From the geometry between the successive mass elements, we see that:

$$\theta_n = \tan^{-1}\left(\frac{-(x_{n+1} - x_n)}{(y_{n+1} - y_n)}\right) \tag{30a}$$

$$\phi_n = \tan^{-1}\left(\frac{(z_{n+1} - z_n)}{\sqrt{(x_{n+1} - x_n)^2 + (y_{n+1} - y_n)^2 + (z_{n+1} - z_n)^2}}\right) \tag{30b}$$

The stretched length between any two mass elements is computed as equal to:

$$\sqrt{(x_{n+1}-x_n)^2+(y_{n+1}-y_n)^2+(z_{n+1}-z_n)^2} \qquad (30c)$$

Figure 12 shows the convention used for the subscripts:

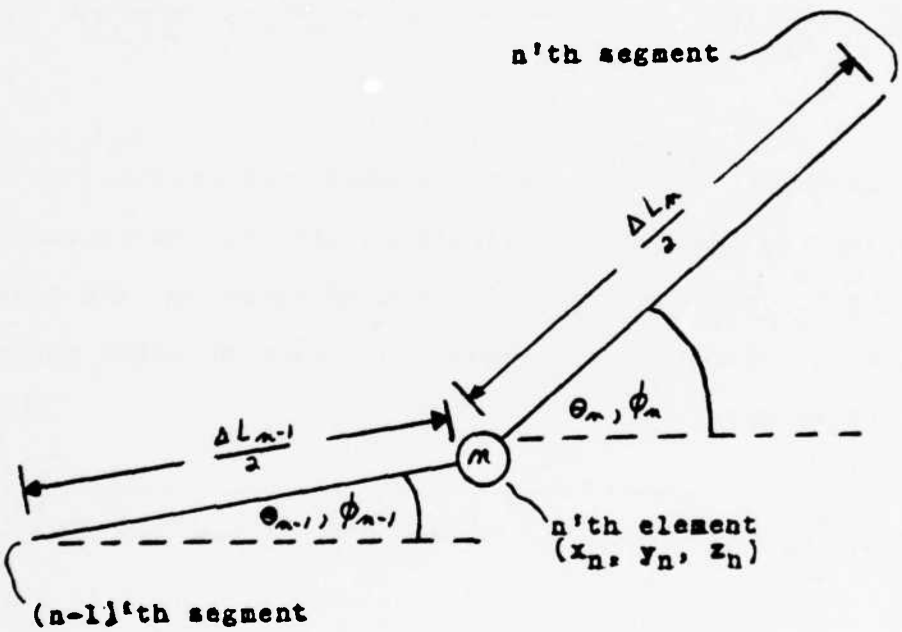

Figure 12. Subscript Convention for Lumped Mass Angles

To compute tensions between elements, the elastic properties of the cable and the cable deformation are used. That is, if the effective cable modulus is E_c and the cable element deformation is δ, then, using Hooke's Law [24], the spring constant along the cable is:

$$K_{y_n''} = \frac{F_n}{\delta_n} = \frac{\left(\frac{\pi d_{s_n}^2}{4}\right)(\sigma_n)}{\delta_n} = \left(\frac{\pi d_{s_n}^2}{4}\right)\left(\frac{E_{c_n}}{\Delta L_n}\right) \tag{31}$$

Assuming the cable cannot support compression, it must be specified that if the difference between the stretched and the unstretched length is zero or negative, the tension is zero. Otherwise, the tension in the n'th cable segment is defined by:

$$T_{y_n'} = K_{y_n'}\left(\sqrt{(x_{n+1}-x_n)^2+(y_{n+1}-y_n)^2+(z_{n+1}-z_n)^2} - \Delta L_n\right) \tag{32}$$

The tension in the inertial coordinate system is, from equation (6):

$$T_n = \begin{bmatrix} -T_{y''_n} \sin\theta_n \cos\phi_n \\ T_{y''_n} \cos\theta_n \cos\phi_n \\ T_{y''_n} \sin\phi_n \end{bmatrix} \tag{33}$$

The inertial tension components are used to compute the tension difference across the mass element given in equation (29).

Each of the forces $\bar{X}_n \Delta L_n$, $\bar{Y}_n \Delta L_n$, and $\bar{Z}_n \Delta L_n$ acting on each mass element consists of weight, viscous drag, and added mass forces. The weight force vector per unit length is, in the inertial coordinate system:

$$W_c = \begin{bmatrix} 0 \\ 0 \\ -w_c \end{bmatrix} \tag{34}$$

where w_c is, as before, the in-water weight per unit length of the cable.

The components of the ocean currents that exist are given as

$$\begin{bmatrix} u \\ v \\ 0 \end{bmatrix} \tag{35}$$

and the velocity components of the n'th element are

$$\begin{bmatrix} \dot{x}_n \\ \dot{y}_n \\ \dot{z}_n \end{bmatrix} \tag{36}$$

then the resultant velocity of the water relative to the cable components are:

$$\begin{bmatrix} U_{Rn} \\ V_{Rn} \\ W_{Rn} \end{bmatrix} = \begin{bmatrix} u - \dot{x}_n \\ v - \dot{y}_n \\ 0 - \dot{z}_n \end{bmatrix} \tag{37}$$

For the purpose of calculating the cable drag and added mass forces, previous studies (6, 9) have used mean cable angles at the n'th element, defined to be:

$$\overline{\theta_n} = \frac{1}{2}\left(\theta_n + \theta_{n-1}\right) \tag{38a}$$

$$\overline{\phi_n} = \frac{1}{2}\left(\phi_n + \phi_{n-1}\right) \tag{38b}$$

Figure 13 shows such angles.

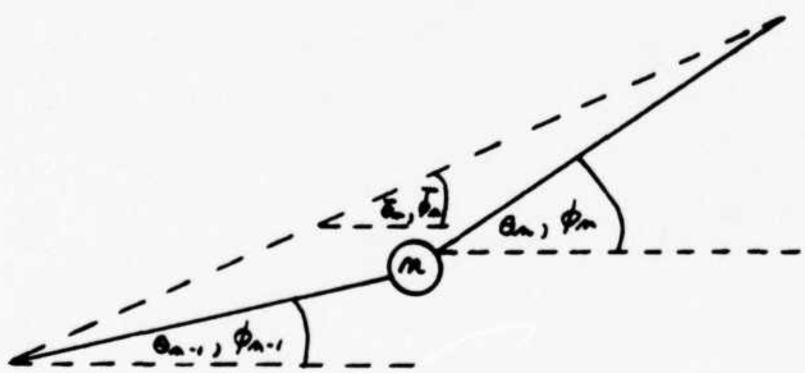

Figure 13. Mean Cable Angles

In using these mean cable angles, it was inherently assumed that the angles θ_{n-1}, θ_n, ϕ_{n-1}, and ϕ_n all lie in the same quadrant of a rectangular Cartesian coordinate system. After examining the preliminary results of the steady state model, however, it was seen that this was not often the case with the present study. Figure 14 shows one such configuration:

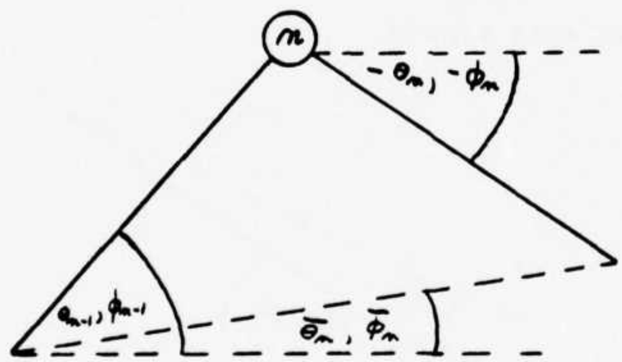

Figure 14. Possible Mean Cable Angles

It is obvious from figure 14 that the mean cable angles computed from equations (38) would yield erroneous results; thus they will not be employed. Rather, the forces considered to be acting at element n will be the summation of those acting on half of the (n-1)'th segment and half of the n'th segment.

The velocity components of the water relative to the cable, using equation (2), are transformed to cable coordinates to yield:

$$U_{R_n''} = (u-\dot{x}_n)(\cos\theta_n) + (v-\dot{y}_n)(\sin\theta_n) \tag{39a}$$

$$V_{R_n''} = -(u-\dot{x}_n)(\sin\theta_n\cos\phi_n) + (v-\dot{y}_n)(\cos\theta_n\cos\phi_n) + (-\dot{z}_n)(\sin\phi_n) \tag{39b}$$

$$W_{R_n''} = (u-\dot{x}_n)(\sin\theta_n\sin\phi_n) - (v-\dot{y}_n)(\cos\theta_n\sin\phi_n) + (-\dot{z}_n)(\cos\phi_n) \tag{39c}$$

The drag force components per unit length are, in cable coordinates:

$$D_{x''_n} = \frac{1}{2} \rho_w d_n c_{DN} \; U_{R''_n} \left| U_{R''_n} \right| \tag{40a}$$

$$D_{y''_n} = \frac{1}{2} \rho_w \pi d_n c_{DT} \; V_{R''_n} \left| V_{R''_n} \right| \tag{40b}$$

$$D_{z''_n} = \frac{1}{2} \rho_w d_n c_{DN} \; W_{R''_n} \left| W_{R''_n} \right| \tag{40c}$$

The drag forces per unit length are then transformed back to inertial coordinates so that they will be consistent with the coordinate system used in the expressions for the other forces.

Lumping the added mass terms with the structural mass terms and transforming from cable coordinates to inertial coordinates yields the added mass matrix:

$$\begin{bmatrix} m_{\ell_{\dot{x}_n}} \cos\theta_n - m_{\ell_{\dot{y}_n}} \sin\theta_n \cos\phi_n + m_{\ell_{\dot{z}_n}} \sin\theta_n \sin\phi_n \\ m_{\ell_{\dot{x}_n}} \sin\theta_n + m_{\ell_{\dot{y}_n}} \cos\theta_n \cos\phi_n - m_{\ell_{\dot{z}_n}} \cos\theta_n \sin\phi_n \\ m_{\ell_{\dot{y}_n}} \sin\phi_n + m_{\ell_{\dot{z}_n}} \cos\phi_n \end{bmatrix} \tag{41}$$

Patton [33] gives the added mass per unit length for very long cylinders as:

$$m_{\ell \ddot{x}_n} = \pi \rho_w \left(\frac{d_n}{2}\right)^2 \tag{42a}$$

$$m_{\ell \ddot{y}_n} = 0 \tag{42b}$$

$$m_{\ell \ddot{z}_n} = \pi \rho_w \left(\frac{d_n}{2}\right)^2 \tag{42c}$$

Then the different terms of the cable equations for the n'th element are as follows.

The mass and added mass terms:

$$\Big\{ \Big[\mu_n(s_0) + m_{\ell \ddot{x}_n} \cos\theta_n - m_{\ell \ddot{y}_n} \sin\theta_n \cos\phi_n + m_{\ell \ddot{z}_n} \sin\theta_n \sin\phi_n \Big] \frac{\Delta L_n}{2} + \Big[\mu_{n-1}(s_0) + m_{\ell \ddot{x}_{n-1}} \cos\theta_{n-1} - m_{\ell \ddot{y}_{n-1}} \sin\theta_{n-1} \cos\phi_{n-1} + m_{\ell \ddot{z}_{n-1}} \sin\theta_{n-1} \sin\phi_{n-1} \Big] \frac{\Delta L_{n-1}}{2} \Big\} \frac{d^2 x_n}{dt^2} \tag{43a}$$

$$\left\{\left[\mu_n(s_0) + m_{\ell x''_n}\sin\theta_n + m_{\ell y''_n}\cos\theta_n\cos\phi_n - m_{\ell z''_n}\cos\theta_n\sin\phi_n\right]\frac{\Delta L_n}{2} + \left[\mu_{n-1}(s_0) + m_{\ell x''_{n-1}}\sin\theta_{n-1} + m_{\ell y''_{n-1}}\cos\theta_{n-1}\cos\phi_{n-1} - m_{\ell z''_{n-1}}\cos\theta_{n-1}\sin\phi_{n-1}\right]\frac{\Delta L_{n-1}}{2}\right\}\frac{d^2 y_n}{dt^2} \tag{43b}$$

$$\left\{\left[\mu_n(s_0) + m_{\ell y''_n}\sin\phi_n + m_{\ell z''_n}\cos\phi_n\right]\frac{\Delta L_n}{2} + \left[\mu_{n-1}(s_0) + m_{\ell y''_{n-1}}\sin\phi_{n-1} + m_{\ell z''_{n-1}}\cos\phi_{n-1}\right]\frac{\Delta L_{n-1}}{2}\right\}\frac{d^2 z_n}{dt^2} \tag{43c}$$

the weight terms:

$$0 \tag{44a}$$

$$0 \tag{44b}$$

$$-\mu_c \tag{44c}$$

the drag terms (after using equation (3) for the transformation from cable to inertial coordinates):

$$\left[D''_{x_n} \cos\theta_n - D''_{y_n} \sin\theta_n \cos\phi_n + D''_{z_n} \sin\theta_n \sin\phi_n\right] \frac{\Delta L_n}{2} + \left[D''_{x_{n-1}} \cos\theta_{n-1} - D''_{y_{n-1}} \sin\theta_{n-1} \cos\phi_{n-1} + D''_{z_{n-1}} \sin\theta_{n-1} \sin\phi_{n-1}\right] \frac{\Delta L_{n-1}}{2} \tag{45a}$$

$$\left[D''_{x_n} \sin\theta_n + D''_{y_n} \cos\theta_n \cos\phi_n - D''_{z_n} \cos\theta_n \sin\phi_n\right] \frac{\Delta L_n}{2} + \left[D''_{x_{n-1}} \sin\theta_{n-1} + D''_{y_{n-1}} \cos\theta_{n-1} \cos\phi_{n-1} - D''_{z_{n-1}} \cos\theta_{n-1} \sin\phi_{n-1}\right] \frac{\Delta L_{n-1}}{2} \tag{45b}$$

$$\left[D''_{y_n} \sin\phi_n + D''_{z_n} \cos\phi_n\right] \frac{\Delta L_n}{2} + \left[D''_{y_{n-1}} \sin\phi_{n-1} + D''_{z_{n-1}} \cos\phi_{n-1}\right] \frac{\Delta L_{n-1}}{2} \tag{45c}$$

and the tension terms:

$$-T_{y''_n} \sin\theta_n \cos\phi_n \qquad (46a)$$

$$T_{y''_n} \cos\theta_n \cos\phi_n \qquad (46b)$$

$$T_{y''_n} \sin\phi_n \qquad (46c)$$

The cable equations, after substituting into (29), are then:

$$\Big\{ \Big[\mu_n(s_0) + m_{\ell_{x''_n}} \cos\theta_n - m_{\ell_{y''_n}} \sin\theta_n \cos\phi_n$$

$$+ m_{\ell_{z''_n}} \sin\theta_n \sin\phi_n \Big] \frac{\Delta L_n}{2} + \Big[\mu_{n-1}(s_0)$$

$$+ m_{\ell_{x''_{n-1}}} \cos\theta_{n-1} - m_{\ell_{y''_{n-1}}} \sin\theta_{n-1} \cos\phi_{n-1}$$

$$+ m_{\ell_{z''_{n-1}}} \sin\theta_{n-1} \sin\phi_{n-1} \Big] \frac{\Delta L_{n-1}}{2} \Big\} \frac{d^2 x_n}{dt^2} =$$

$$\Big[\Big(D_{x''_n} \cos\theta_n - D_{y''_n} \sin\theta_n \cos\phi_n$$

$$+ D_{z''_n} \sin\theta_n \sin\phi_n \Big) \frac{\Delta L_n}{2} + \Big(D_{x''_{n-1}} \cos\theta_{n-1}$$

$$- D_{y''_{n-1}} \sin\theta_{n-1} \cos\phi_{n-1} + D_{z''_{n-1}} \sin\theta_{n-1} \sin\phi_{n-1} \Big) \frac{\Delta L_{n-1}}{2} \Big]$$

$$+ \left(-T_{y''_n} \sin\theta_n \cos\phi_n + T_{y''_{n-1}} \sin\theta_{n-1} \cos\phi_{n-1} \right) \qquad (47a)$$

$$\Big\{ \Big[\mu_n(s_0) + m_{\ell x_n''} \sin\theta_n + m_{\ell y_n''} \cos\theta_n \cos\phi_n$$

$$- m_{\ell z_n''} \cos\theta_n \sin\phi_n \Big] \frac{\Delta L_n}{2} + \Big[\mu_{n-1}(s_0)$$

$$+ m_{\ell x_{n-1}''} \sin\theta_{n-1} + m_{\ell y_{n-1}''} \cos\theta_{n-1} \cos\phi_{n-1}$$

$$- m_{\ell z_{n-1}''} \cos\theta_{n-1} \sin\phi_{n-1} \Big] \frac{\Delta L_{n-1}}{2} \Big\} \frac{d^2 y_n}{dt^2} =$$

$$\Big[\Big(D_{x_n''} \sin\theta_n + D_{y_n''} \cos\theta_n \cos\phi_n$$

$$- D_{z_n''} \cos\theta_n \sin\phi_n \Big) \frac{\Delta L_n}{2} + \Big(D_{x_{n-1}''} \sin\theta_{n-1}$$

$$+ D_{y_{n-1}''} \cos\theta_{n-1} \cos\phi_{n-1} - D_{z_{n-1}''} \cos\theta_{n-1} \sin\phi_{n-1} \Big) \frac{\Delta L_{n-1}}{2} \Big]$$

$$+ \Big(T_{y_n''} \cos\theta_n \cos\phi_n - T_{y_{n-1}''} \cos\theta_{n-1} \cos\phi_{n-1} \Big) \qquad (47b)$$

$$\Big\{ \Big[\mu_n(s_0) + m_{\ell y_n''} \sin\phi_n + m_{\ell z_n''} \cos\phi_n \Big] \frac{\Delta L_n}{2}$$

$$+ \Big[\mu_{n-1}(s_0) + m_{\ell y_{n-1}''} \sin\phi_{n-1} + m_{\ell z_{n-1}''} \cos\phi_{n-1} \Big] \frac{\Delta L_{n-1}}{2} \Big\} \frac{d^2 z_n}{dt^2} =$$

$$\Big[-(w_c)\Big(\frac{\Delta L_n}{2}\Big) + -(w_c)\Big(\frac{\Delta L_{n-1}}{2}\Big) \Big] + \Big[\Big(D_{y_n''} \sin\phi_n + D_{z_n''} \cos\phi_n \Big) \frac{\Delta L_n}{2}$$

$$+ \Big(D_{y_{n-1}''} \sin\phi_{n-1} + D_{z_{n-1}''} \cos\phi_{n-1} \Big) \frac{\Delta L_{n-1}}{2} \Big]$$

$$+ \Big(T_{y_n''} \sin\phi_n - T_{y_{n-1}''} \sin\phi_{n-1} \Big) \qquad (47c)$$

The auxiliary relations are:

$$\theta_n = \tan^{-1}\left[\frac{-(x_{n+1} - x_n)}{(y_{n+1} - y_n)}\right] \tag{48a}$$

$$\phi_n = \tan^{-1}\left[\frac{(z_{n+1} - z_n)}{\sqrt{(x_{n+1} - x_n)^2 + (y_{n+1} - y_n)^2 + (z_{n+1} - z_n)^2}}\right] \tag{48b}$$

$$T_{y''_n} = K_{y'_n}\left(\sqrt{(x_{n+1} - x_n)^2 + (y_{n+1} - y_n)^2 + (z_{n+1} - z_n)^2} - \Delta L_n\right) \tag{48c}$$

$$K_{y'_n} = \left(\frac{\pi d_{3n}^2}{4}\right)\left(\frac{E_{cn}}{\Delta L_n}\right) \tag{48d}$$

3.2 Subsurface Buoy Dynamics

The forces acting on the subsurface buoy are

a. an external gravitational force,

b. hydrostatic forces,

c. hydrodynamic forces (drag and added mass), and

d. cable tensions

Using Newton's Second Law, [34] the equations of motion for the subsurface buoy can be developed. In matrix form, the equations of motion are:

$$\mathbb{M}\ddot{\mathbb{Q}} = \mathbb{M}\mathbb{G} - \mathbb{B} - \mathbb{H} - \mathbb{T} \tag{49a}$$

or

$$\mathbb{M}\ddot{\mathbb{Q}} = \mathbb{W} - \mathbb{H} - \mathbb{T} \tag{49b}$$

where

$\mathbb{M}$ = the structural mass matrix

$\ddot{\mathbb{Q}}$ = the acceleration vector

$\mathbb{G}$ = the gravitational vector

$\mathbb{B}$ = the hydrostatic force vector

$\mathbb{H}$ = the hydrodynamic force vector

$\mathbb{T}$ = the cable tension vector

$\mathbb{W}$ = the body weight in water vector

The structural mass matrix can be written as:

$$M = \begin{bmatrix} m & 0 & 0 \\ 0 & m & 0 \\ 0 & 0 & m \end{bmatrix} \tag{50}$$

where m is the mass of the buoy.

The acceleration vector is:

$$\ddot{Q} = \begin{bmatrix} \ddot{x}_c \\ \ddot{y}_c \\ \ddot{z}_c \end{bmatrix} \tag{51}$$

where x_c, y_c, and z_c are the x, y, and z coordinates of the center of the buoy.

The in water weight vector is:

$$W = \begin{bmatrix} 0 \\ 0 \\ -w_l \end{bmatrix} \tag{52}$$

(Note that $(-w_b)$ will be positive for a positively buoyant buoy.)

The tension vector is:

$$\mathrm{T} = \begin{bmatrix} -T_S \sin\theta_S \cos\phi_S + T_R \sin\theta_R \cos\phi_R \\ T_S \cos\theta_S \cos\phi_S - T_R \cos\theta_R \cos\phi_R \\ T_S \sin\phi_S - T_R \sin\phi_R \end{bmatrix} \quad (53)$$

where T_S and T_R are the tension magnitudes of the cable segments above and below the buoy respectively (see equation (32)), and θ_S, ϕ_S, θ_R, and ϕ_R are the horizontal and vertical angles of these segments as defined in equation (30).

The hydrodynamic forces acting upon the buoy are caused by the motion of the body in the fluid. These forces are considered to be inertial (added mass) and dissipative. Dissipative forces caused by viscosity will be discussed as separate force components, as will the inertial forces caused by buoy motion.

The added mass matrix is established as follows, where the off-diagonal terms have been taken to be zero due to the

symmetry of the buoy:

$$M_l = \begin{bmatrix} m_{l_x} & 0 & 0 \\ 0 & m_{l_y} & 0 \\ 0 & 0 & m_{l_z} \end{bmatrix} \tag{54}$$

Patton [33] gives the hydrodynamic mass for a sphere of radius R_S as:

$$m_{l_x} = \frac{2}{3} \pi \rho_w (R_s)^2 \tag{55a}$$

$$m_{l_y} = \frac{2}{3} \pi \rho_w (R_s)^2 \tag{55b}$$

$$m_{l_z} = \frac{2}{3} \pi \rho_w (R_s)^2 \tag{55c}$$

The viscous force matrix may be given as:

$$D = \begin{bmatrix} D_{B_x} \\ D_{B_y} \\ D_{B_z} \end{bmatrix} \tag{56}$$

or

$$\mathbb{D} = \begin{bmatrix} \frac{1}{2} \rho_w C_{DS} (\pi R_s^2) (U_{RN}) (|U_{RN}|) \\ \frac{1}{2} \rho_w C_{DS} (\pi R_s^2) (V_{RN}) (|V_{RN}|) \\ \frac{1}{2} \rho_w C_{DS} (\pi R_s^2) (W_{RN}) (|W_{RN}|) \end{bmatrix} \quad (57)$$

Hydrodynamic forces are computed by considering water mass movements relative to the body. Assume that the buoy is deep enough so it is not influenced by surface waves and that the water mass movement is some steady flow resulting from steady ocean currents. Then the relative acceleration of the water mass surrounding the buoy is given in equation (51) as:

$$\ddot{Q} = \begin{bmatrix} \ddot{x}_c \\ \ddot{y}_c \\ \ddot{z}_c \end{bmatrix} \quad (58)$$

The velocity vector of the body relative to the water mass is defined in equation (37) to be:

$$\dot{Q} = \begin{bmatrix} U_{RN} \\ V_{RN} \\ W_{RN} \end{bmatrix} \tag{59}$$

The equations of motion for the buoy can be summarized as:

$$\mathcal{M}\ddot{Q} = \mathcal{W} - \mathcal{H} - \mathcal{T} \tag{60}$$

Substituting for the hydrodynamic forces

$$\mathcal{H} = \mathcal{M}_{\ell}\ddot{Q} + \mathbb{D} \tag{61}$$

yields

$$\mathcal{M}\ddot{Q} = \mathcal{W} - \mathcal{M}_{\ell}\ddot{Q} - \mathcal{D} - \mathcal{T} \tag{62}$$

which simplifies to

$$(M + M_\ell)\,\ddot{Q} = W - D - T \tag{63}$$

with all the coefficients as previously discussed.

The inertial term becomes:

$$\begin{bmatrix} (m + m_{\ell x})\,\ddot{x}_c \\ (m + m_{\ell y})\,\ddot{y}_c \\ (m + m_{\ell z})\,\ddot{z}_c \end{bmatrix} \tag{64}$$

The viscous force term is:

$$\begin{bmatrix} D_{\ell x} \\ D_{\ell y} \\ D_{\ell z} \end{bmatrix} \tag{65}$$

The weight term becomes:

$$\begin{bmatrix} 0 \\ 0 \\ -w_\ell \end{bmatrix} \tag{66}$$

The tension term is:

$$\begin{bmatrix} -T_S \sin\theta_S \cos\phi_S + T_R \sin\theta_R \cos\phi_R \\ T_S \cos\theta_S \cos\phi_S - T_R \cos\theta_R \cos\phi_R \\ T_S \sin\phi_S - T_R \sin\phi_R \end{bmatrix} \qquad (67)$$

As was shown in figures 10 and 11, a buoy is located at the exact position of one of the cable mass elements. Thus, the equilibrium equations for the buoy will not be solved explicitly, but rather the inertial, viscous, and weight terms of equations (64), (65), and (66) respectively will be added to the inertial, viscous, and weight terms of the cable element of equations (43), (45), and (44) respectively for the appropriate lumped mass. This will give one set of equations for the element, with the forces acting on the cable and buoy lumped together for the solution.

3.3 <u>Ship Motions</u>

In order to determine the ship motions resulting from waves, M.I.T.'s five degrees of freedom seakeeping program [35] (surge neglected) was used. This program is based upon the theory developed by Salvesen,[36] and employs the section transformations used by Loukakis.[37] Appendix D gives a detailed description of the ship used in the present

study.

The ship positions are given in the inertial coordinate system centered at the anchor as follows:

$$x_7 = \sum_{i=0}^{100} S_{hx_i} \sin(\omega_i t + \varepsilon_{x_i}) \tag{68a}$$

$$y_7 = G \tag{68b}$$

$$z_7 = H + \sum_{i=0}^{100} S_{hz_i} \sin(\omega_i t + \varepsilon_{z_i}) \tag{68c}$$

where

$S_{h_{x_1}}$, $S_{h_{z_1}}$ = amplitude of lateral and vertical motion of ship's point of attachment to cable

ω_1 = the wave frequency

ε_{x_1}, ε_{z_1} = the phase angles

Velocities at the ship are found by differentiation of equations (68) with respect to time:

$$\dot{x}_7 = \sum_{i=0}^{100} S_{hx_i} \omega_i \cos(\omega_i t + \varepsilon_{x_i}) \tag{69a}$$

$$\dot{y}_7 = 0 \tag{69b}$$

$$\dot{z}_7 = \sum_{i=0}^{100} S_{\ell z_i} w_i \cos(w_i t + \varepsilon_{z_i}) \tag{69c}$$

Accelerations at the ship may be obtained by differentiating the velocities of equations (69) with respect to time:

$$\ddot{x}_7 = -\sum_{i=0}^{100} S_{\ell x_i} w_i^2 \sin(w_i t + \varepsilon_{x_i}) \tag{70a}$$

$$\ddot{y}_7 = 0 \tag{70b}$$

$$\ddot{z}_7 = -\sum_{i=0}^{100} S_{\ell z_i} w_i^2 \sin(w_i t + \varepsilon_{z_i}) \tag{70c}$$

In order to calculate $S_{h_{x_1}}$, ε_{x_1}, $S_{h_{z_1}}$, and ε_{z_1}, the following method was used:

First, the spectra of the vertical motion and lateral motion of the point of interest for each sea state examined was calculated and punched out on cards. These calculations

were performed at selected frequencies so as to have complete coverage of the spectrum of interest. The computations were performed by a modified version of M.I.T.'s seakeeping program.[35]

Second, each spectrum was transformed into a time series by selecting frequencies such that

$$\omega_i = a(i-1)^2 + \omega_{min} \qquad i = 1, 2, \ldots, n, n+1$$

where

$$a = \frac{(\omega_{max} - \omega_{min})}{n^2}$$

n = number of subdivisions

ω_{min} = minimum ω of spectrum definition

ω_{max} = maximum ω of spectrum definition

Each element of the time series was of the form:

$$A_i = \sin(\omega_i t + \varepsilon_{z_i})$$

where

$$A_i = \sqrt{(2 * \text{spectral ordinata}_{i+1} * (\omega_{i+1} - \omega_i))}$$

t = time

ε_{z_i} = phase angle generated randomly

The complete time series was of the form:

$$\sum_{i=1}^{n+1} A_i \sin (\omega_i t + \epsilon_{z_i})$$

Finally, the relation between ϵ_{x_1} and ϵ_{z_1} was determined using the regular wave results of the vertical and lateral motion.

Appendix F lists the values of ω_1, $S_{h_{x_1}}$, ϵ_{x_1}, $S_{h_{z_1}}$, and ϵ_{z_1} for each of the ship headings. (Chepter 4 describes the three ship headings and the particular sea state used for the calculations made in this study.)

3.4 Numerical Solution of Equations for Lumped-Mass System

The lumped-mass system has been assumed to consist of seven lumped-masses. (The anchor is element number one; the ship is element number seven.) At each element, three non-linear second order differential equations may be written. This yields twenty one second order equations to describe the system.

In order to solve these equations, the fourth-order Runge-Kutta method [25] used in section 2.1 is again applied.

The inertial coordinates of each element in the steady state model are used as the initial conditions (time = o) for the dynamic model. The anchor is always located at the origin of the coordinate system; velocities and accelerations at this point are thus always zero. The location, velocity, and acceleration of the ship are given by equations (68), (69), and (70) respectively. Locations, velocities, and accelerations of the other elements are calculated from equations (47), (48), (64), (65), and (66).

As noted by Patton,[9] the system's highest natural frequency is, in general, in the axial mode and along the strength member of the cable. An estimate of this value may be given by:

$$f_n = \frac{1}{2\pi}\sqrt{\left(\frac{2 E_{c_n} A_n}{\mu_n \Delta L_n}\right)} \tag{71}$$

where

$E_{c_n}A_n$ = the product of the strength member's effective elastic modulus and effective cross-sectional area (see figure 1),

μ_n = the cable's mass per unit length,

L_n = the unstretched length of cable between two successive mass elements.

After the highest natural frequency has been computed, the integration step size in the time domain should be approxi-

mately 1/20 of the shortest period, i.e., to insure numerical stability:

$$b = 0.05 \left(\frac{1}{f_h}\right) \qquad (72)$$

IV. RESULTS

Computations made through the implementation of the computer program described in this study may be used to design particular cable-buoy-ship systems. The system of interest here is subjected to certain operational constraints and design requirements, which are given below. This does not imply that the simulation is constrained, but rather, for this example, just certain physical paremeters are constrained.

Some parameters of the system components, such as cable properties, are fixed because they had been previously specified in the original design of the entire system. Others, such as the current profile, are considered to represent the "worst case condition" for the operating area of interest. These invariant system parameters are presented in Table 1,* where the terms used are defined in section C.5 of Appendix C.

The following constraints on the behavior of the system modeled have been imposed:

* Tables 1-5 and figures 15-34 are presented at the end of this chapter.

a. the steady state tension at the anchor must not exceed 1000 pounds,

b. the maximum steady state tension at any point along the cable must not exceed 5000 pounds,

c. the depth of the buoy or buoys must be minimized so that the buoys may be constructed out of inexpensive materials,

d. the number of buoys used in the system must be minimized for greater ease in handling and reduced costs,

e. the ship must be able to operate at horizontal ranges varying from 4000 feet to 12,000 feet from the anchor, and

f. sufficient decoupling of the wave-induced motions of the ship from the cable must take place up to and including sea state four.

(Note the magnitude of the tension at the anchor is not checked for the dynamic case because element number one is too long, about 5500 feet in this case.)

It should be noted these constraints are not necessary for other moored systems. Suppose, for example, that the following process is employed for the cable-buoy-anchor deployment. The system is layed out in a line on the ocean surface, anchor first, with appropriate buoyancy added to the anchor to keep it afloat. After the entire system has been layed out, the extra buoyancy at the anchor is jettisoned, and the system is allowed to free-fall to the bottom. If the cable is very long and is negatively buoyant, then problems may be encountered while it is being deployed on

the surface if there is only one buoy. With one buoy, the system would assume a "ω" shape. If more buoys were added, however, the deep catenaries would be minimized and the cable would assume more of a straight line configuration on or near the surface. Thus, for this type of system, requirement (d) would have to be modified.

Previous experience [38] has indicated that the bulk of the design of systems similar to the one being considered in the present study can be made primarily from detailed and numerous steady state calculations. After the system has been selected, however, its dynamic behavior must be checked. This plan has been followed here. Cases 1 to 11 are steady state simulations only; cases 12 to 14 are dynamic simulations. Table 2 summarizes which system parameters were varied for each case. (The terms used in table 2 are defined in section C.5 of Appendix C.) Figures 15 through 25 show three dimensional plots of the configurations of cases 1 to 11 respectively.

Cases 1 to 5 vary the horizontal distance between the anchor and the ship from 4000 feet to 12,000 feet. The significant results are presented in tables, 3, 4, and 5, where T, Θ, and ϕ are defined in section 2.1, and the coordinates x_E, y_E, and z_E and the subscripts BE and BD are defined in figure 7 of section 2.2.1. It can be seen that the highest

tension at the anchor, the maximum tension (which is always T_{BS} of the first buoy), and the largest buoy depth all occur when the ship is 12,000 feet from the anchor (case 5). Thus, since this appears to be a "worst case" condition, subsequent cases assume this value to be fixed.

Cases 6 to 8 examine the effects of varying the excess buoyancy of the single buoy configuration; cases 9 to 11 divide the one buoy into two buoys such that the sum of the excess buoyancies of the two buoys of cases 9, 10, and 11 is identical to that of the one buoy of cases 6, 7, and 8 respectively. Maximum tensions are acceptable for all the cases. The tension at the anchor is above the 1000 pound limit for cases 8 and 11. Comparable cases indicate that the anchor tension is slightly lower for the two buoy cases compared to the one buoy cases. The buoy depth for the second buoy (buoy closest to the ship) in cases 9 and 10 is deeper than that of the single buoy of cases 6 and 7 respectively. (Even if the lower buoy of cases 9 or 10 were moved up the cable, the second buoy would always be deeper than the one of cases 6 or 7 until it reached the second buoy, at which point cases 9 and 10 would reduce to cases 6 and 7 respectively.)

Thus, the only advantage of the two buoy configuration is a slight reduction of tension at the anchor. It was

decided by Brown and Griffin[38] that this benefit was not enough to justify adding complexity to the system, since there would be a second buoy. By increasing the cost of the buoys, there would not only be two of them, but also they would have to be constructed out of more expensive materials.

A choice then had to be made between the lower anchor tension of case 6 and the shallower buoy depth of case 7. Since the buoy of case 6 was over 500 feet deeper than that of case 7, and since the anchor tension of case 7 was in the acceptable range, case 7 was chosen as the optimal compromise system. This configuration satisfied the first five specifications mentioned earlier; the sixth and final requirement will now be checked.

The ship is assumed to be influenced by fully developed seas driven by 20 knot winds (significant wave height of 8 feet, sea state four), which is expected to be the worst conditions encountered during operations. (If conditions worsen, operations are ceased for this particular system.) Case 12 assumes beam seas, case 14 assumes head seas, and case 13 assumes a heading of 135° (bow quartering seas) in between cases 12 and 14.

Figures 26, 27, and 28 plot the lateral and vertical motions of the bow of the ship at the point of the cable attachment versus time for each case. Only a 50 second inter-

val of the 2000 second simulation is shown here. Figures 29, 30, and 31 show the tension in segment number one (the anchor) and the tension in segment number six (the ship) as functions of time for each case. (See figure 10 for a sketch of this system.) Figures 32, 33, and 34 plot the tension in segment number three (just below the buoy) and the tension in segment number four (just above the buoy) versus time for each case.

Figures 26, 27, and 28 compare the ship's response in lateral and vertical motions for the identical sea state for three different ship headings. It is seen that the ship is stimulated most in case 13 (heading halfway between beam and head seas). Thus, one would expect that the tensions encountered in the system would be worst for this case. (This assumption will now be checked.)

In examining figures 29, 30, and 31 it can be seen that the above assumption holds: case 13 does show the largest tension variations at the ship. Tensions at the anchor, however, are similar for cases 13 and 14. Therefore, case 14 must also be carefully looked at.

The purpose of this study is to decouple the cable motions of the section below the buoy from the wave-induced motions of the upper section. Figures 32, 33, and 34 can be used to see how effective this decoupling mechanism is. It

is clear from these plots that this system does indeed fulfill this requirement. While large variations are seen in segment number 4, much smaller variations in tension are seen in segment number 3. (The behavior of segment three is typical of those below the buoy; the behavior of segment four is typical of those above the buoy.)

TABLE

EAD	=	2.309×10^6
EEG	=	2.309×10^6
EGT	=	2.309×10^6
WAD	=	0.145
WEG	=	0.145
WGT	=	0.145
DAD	=	1.950
DEG	=	1.950
DGT	=	1.950
DSAD	=	0.622
DSEG	=	0.622
DSGT	=	0.622

CURRENT

H	=	17,700
CX	=	0.5
D	=	300
CY	=	0.3
CB	=	0
THEC	=	270

Table 1. Invariant System Parameters

CASE NO.	BUOY PARAMETERS					CABLE PARAMETERS			SHIP PARAMETERS	
	IBUOY	RA	PA	RB	PB	SAD	SEG	SGT	G	BETA
1	1	3100	26			16,700	6300		4000	
2	1	3100	26			16,700	6300		6000	
3	1	3100	26			16,700	6300		8000	
4	1	3100	26			16,700	6300		10,000	
5	1	3100	26			16,700	6300		12,000	
6	1	2700	26			16,700	6300		12,000	
7	1	3100	26			16,700	6300		12,000	
8	1	3500	26			16,700	6300		12,000	
9	2	1350	32	1350	26	8360	8340	6300	12,000	
10	2	1550	32	1550	26	8360	8340	6300	12,000	
11	2	1750	32	1750	26	8360	8340	6300	12,000	
12	1	3100	26			16,700	6300		12,000	90
13	1	3100	26			16,700	6300		12,000	135
14	1	3100	26			16,700	6300		12,000	180

Table 2. Variable System Parameters

CASE NO.	ANCHOR			FIRST BUOY					
	T	Θ	ϕ	T_{BE}	Θ_{BE}	ϕ_{BE}	T_{BD}	Θ_{BD}	ϕ_{BD}
1	361	-57.1	59.9	2739	-2.3	87.8	378	-0.9	-73.8
2	395	-42.9	55.9	2757	1.8	86.1	396	2.6	-62.0
3	469	-29.4	50.1	2796	3.3	84.1	429	3.8	-48.1
4	610	-18.5	44.4	2879	3.3	81.4	500	3.6	-30.5
5	914	-10.0	40.5	3091	2.4	77.0	700	2.6	- 7.2
6	585	-10.6	21.2	2687	3.6	78.3	549	3.8	- 7.2
7	914	-10.0	40.5	3091	2.4	77.0	700	2.6	- 7.2
8	1331	- 8.9	49.7	3540	1.7	75.9	863	1.9	- 4.4
9	381	-15.1	29.5	1436	-12.0	76.7	334	-11.9	8.2
10	697	-14.9	51.9	1810	-12.1	76.3	477	-12.1	25.8
11	1090	-13.6	60.4	2223	-11.2	76.0	674	-11.2	37.1

Table 3. Steady State Tensions and Angles at Anchor and First Buoy

CASE NO.	SECOND BUOY						SHIP		
	T_{BE}	θ_{BE}	ϕ_{BE}	T_{BD}	θ_{BD}	ϕ_{BD}	T	θ	ϕ
1							555	60.5	72.4
2							590	49.3	68.1
3							658	39.3	62.4
4							787	29.7	56.0
5							1079	20.0	49.7
6							1004	24.4	56.7
7							1079	20.0	49.7
8							1208	16.5	44.5
9	1300	7.6	75.3	344	7.8	-15.7	882	36.4	66.5
10	1481	5.0	73.2	449	5.2	-17.2	890	30.0	60.4
11	1703	3.3	71.6	553	3.5	-14.0	946	24.8	55.0

Table 4. Steady State Tensions and Angles at Second Buoy and Ship

CASE NO.	FIRST BUOY				SECOND BUOY			
	x_B	y_B	z_B	DEPTH	x_B	y_B	z_B	DEPTH
1	1936	1409	16,457	1243				
2	1851	2319	16,340	1360				
3	1668	3514	16,102	1598				
4	1356	4938	15,704	1996				
5	938	6655	15,075	2625				
6	1074	7065	14,542	3158				
7	938	6655	15,075	2625				
8	791	6440	15,305	2395				
9	929	3568	7298	10,402	1423	7862	13,979	3725
10	778	3040	7703	9997	1296	7265	14,645	3055
11	646	2781	7852	9848	1123	6902	14,971	2729

Table 5. Positions of First Buoy and Second Buoy

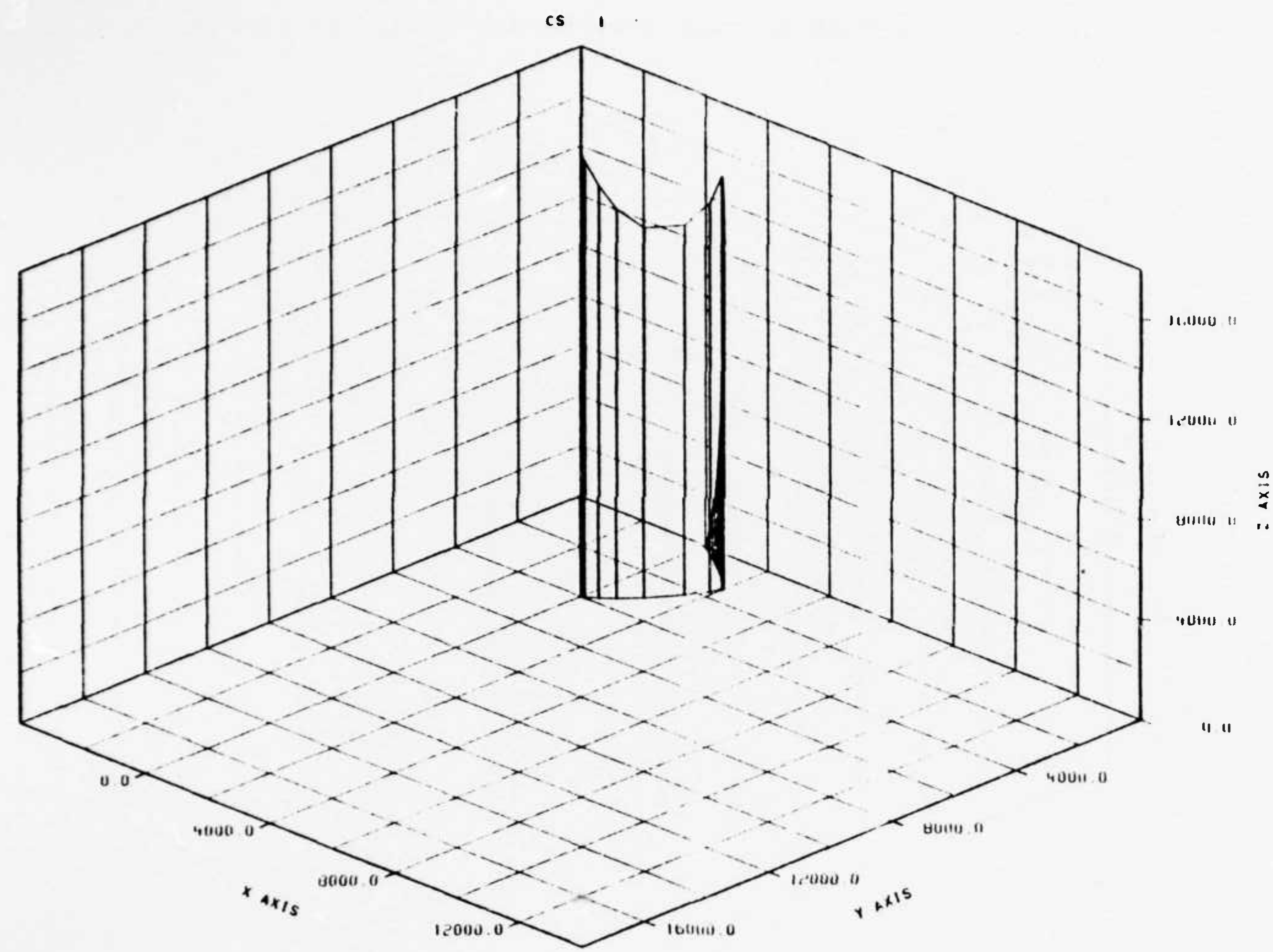

Figure 15. Three Dimensional Plot of Case 1

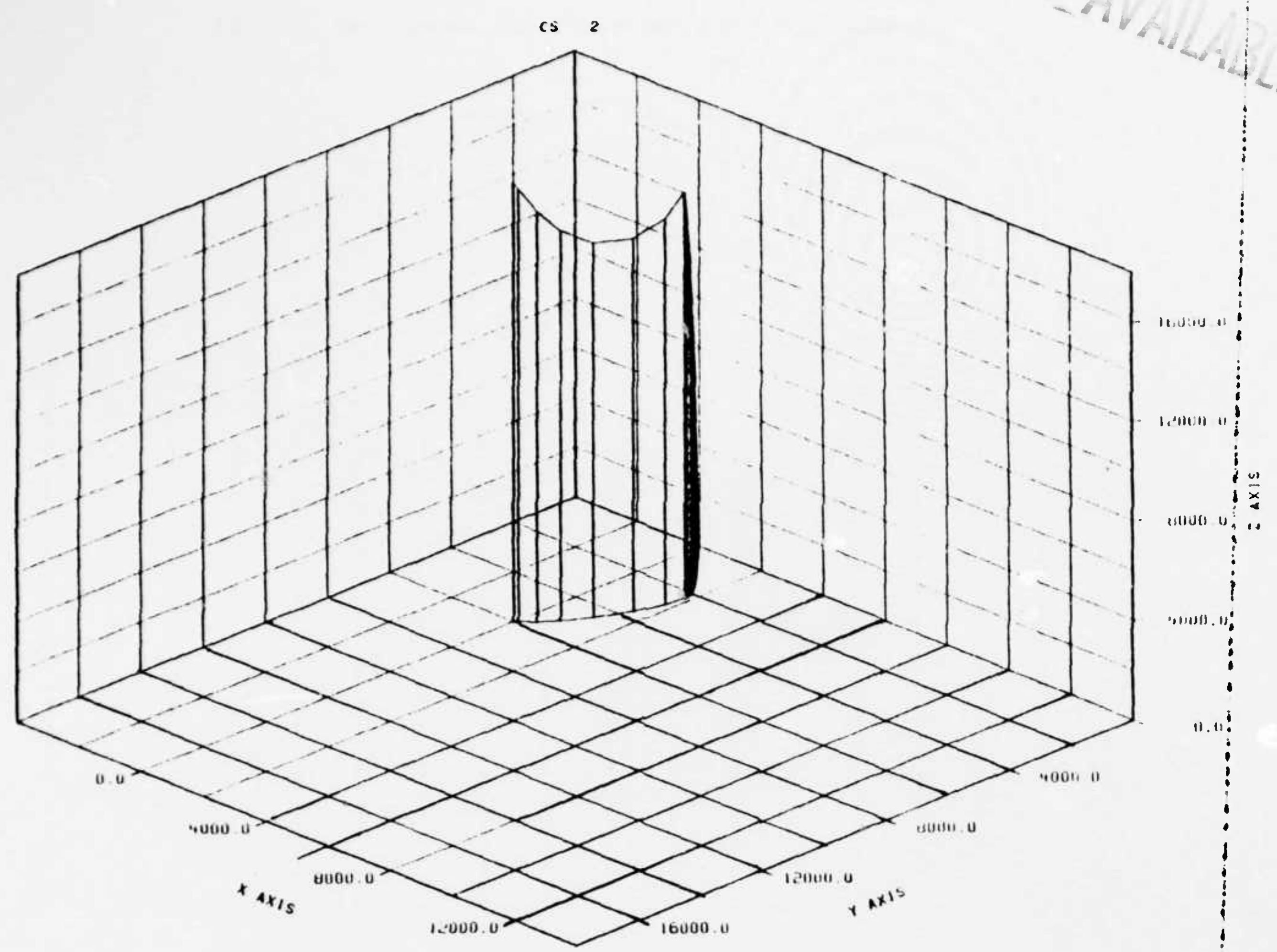

Figure 16. Three Dimensional Plot of Case 2

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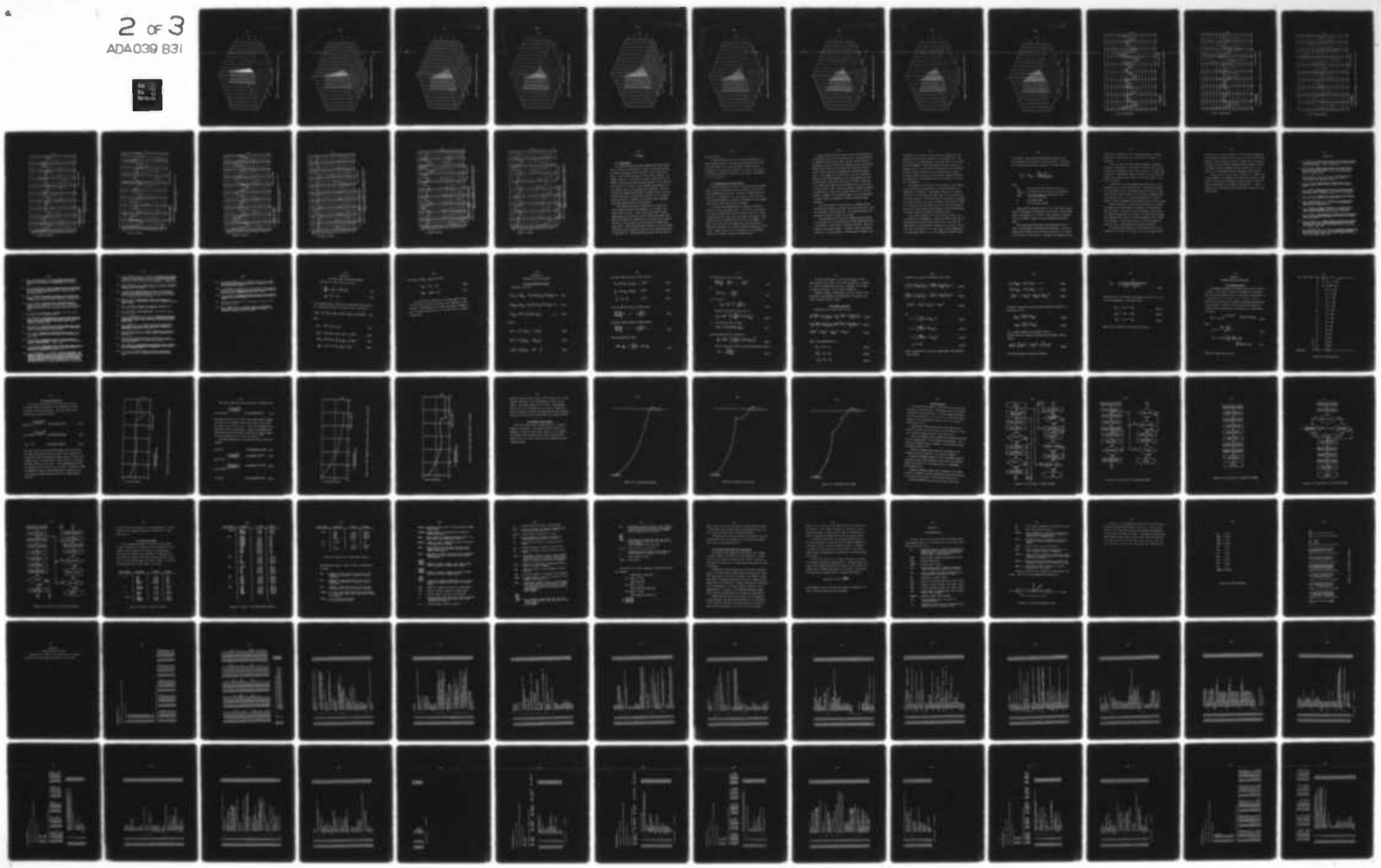

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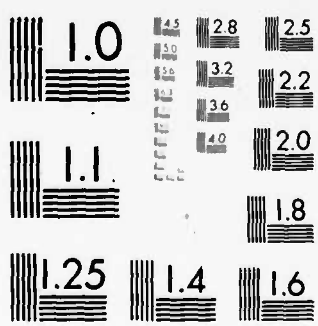


MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS 1963-A

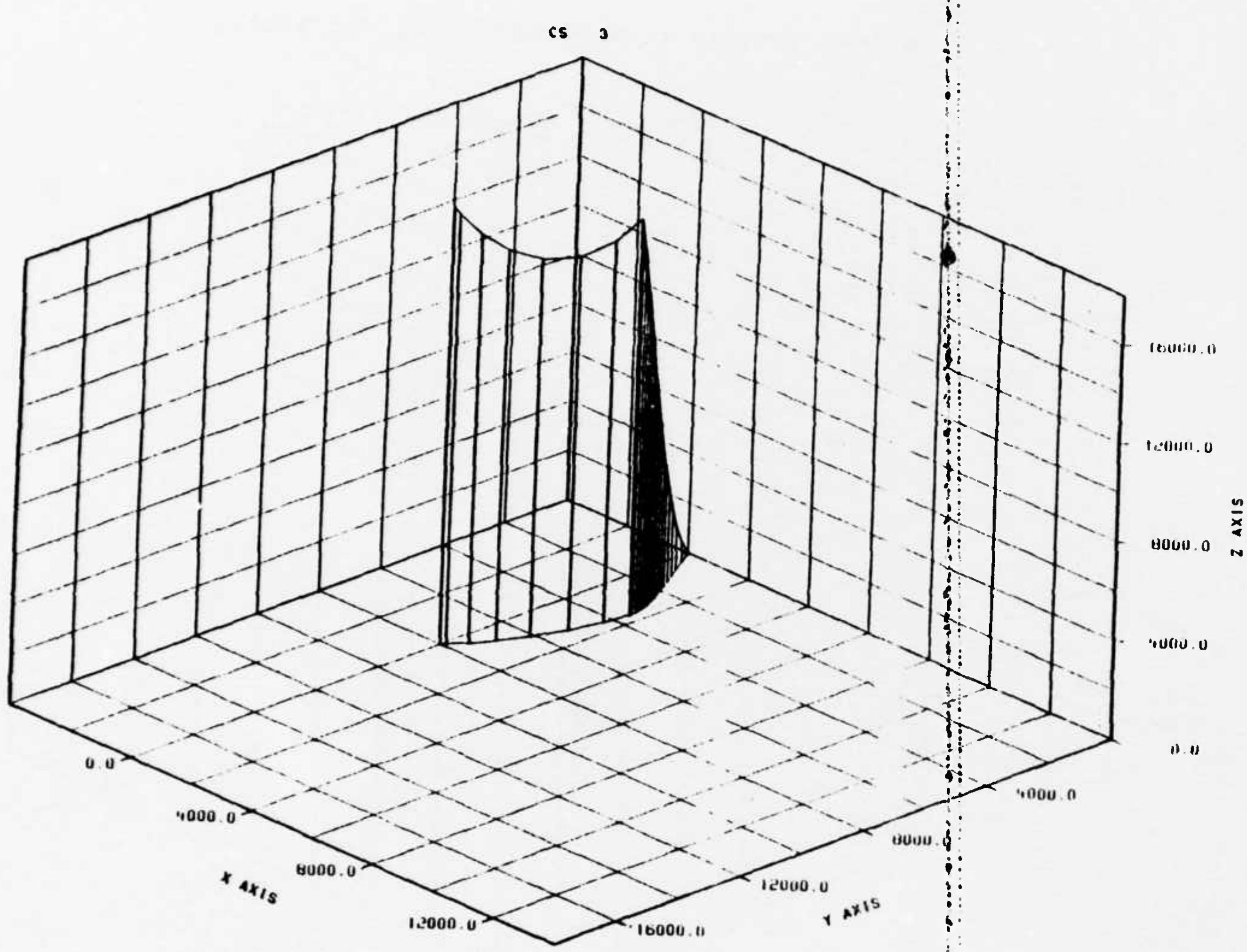


Figure 17. Three Dimensional Plot of Case 3

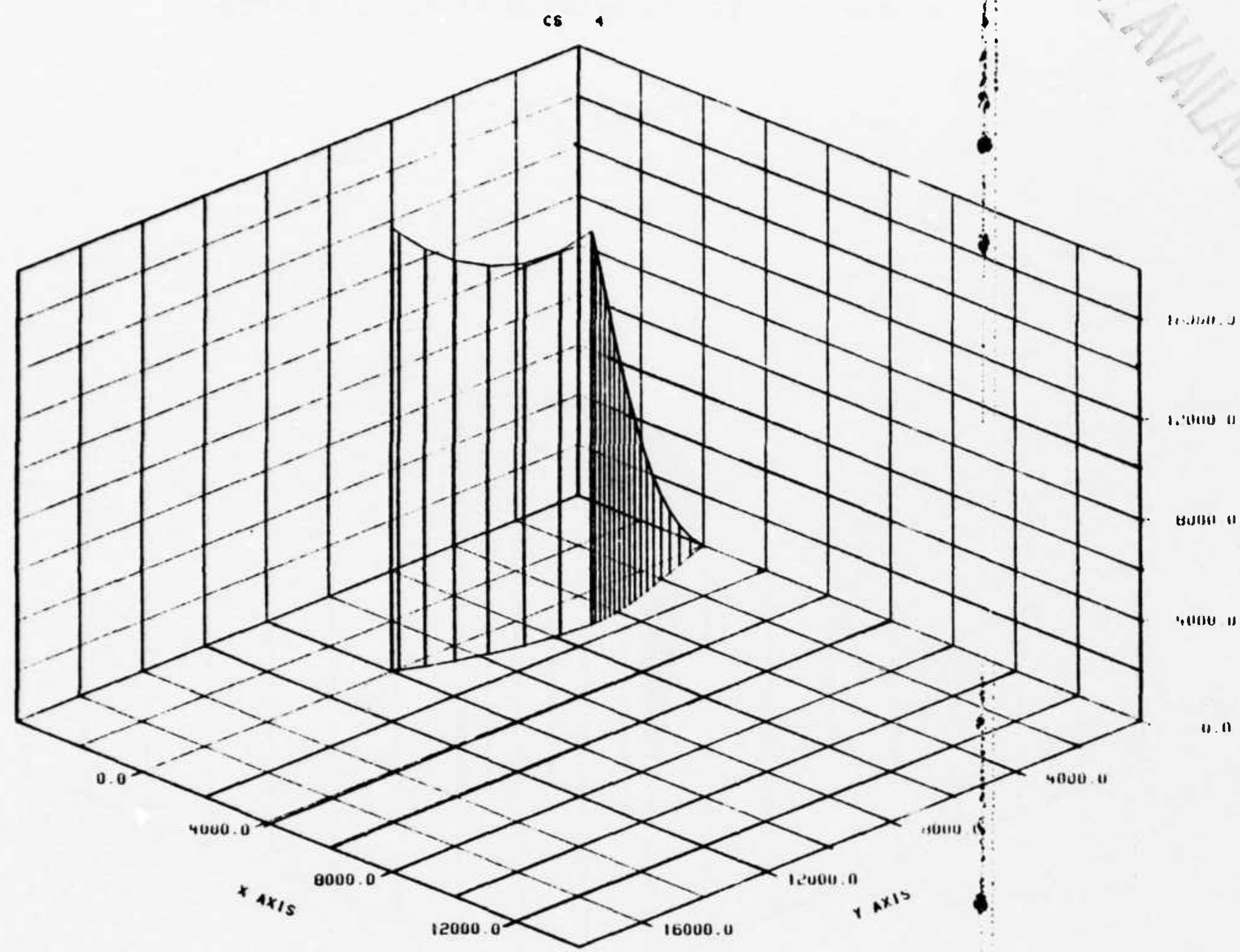


Figure 18. Three Dimensional Plot of Case 4

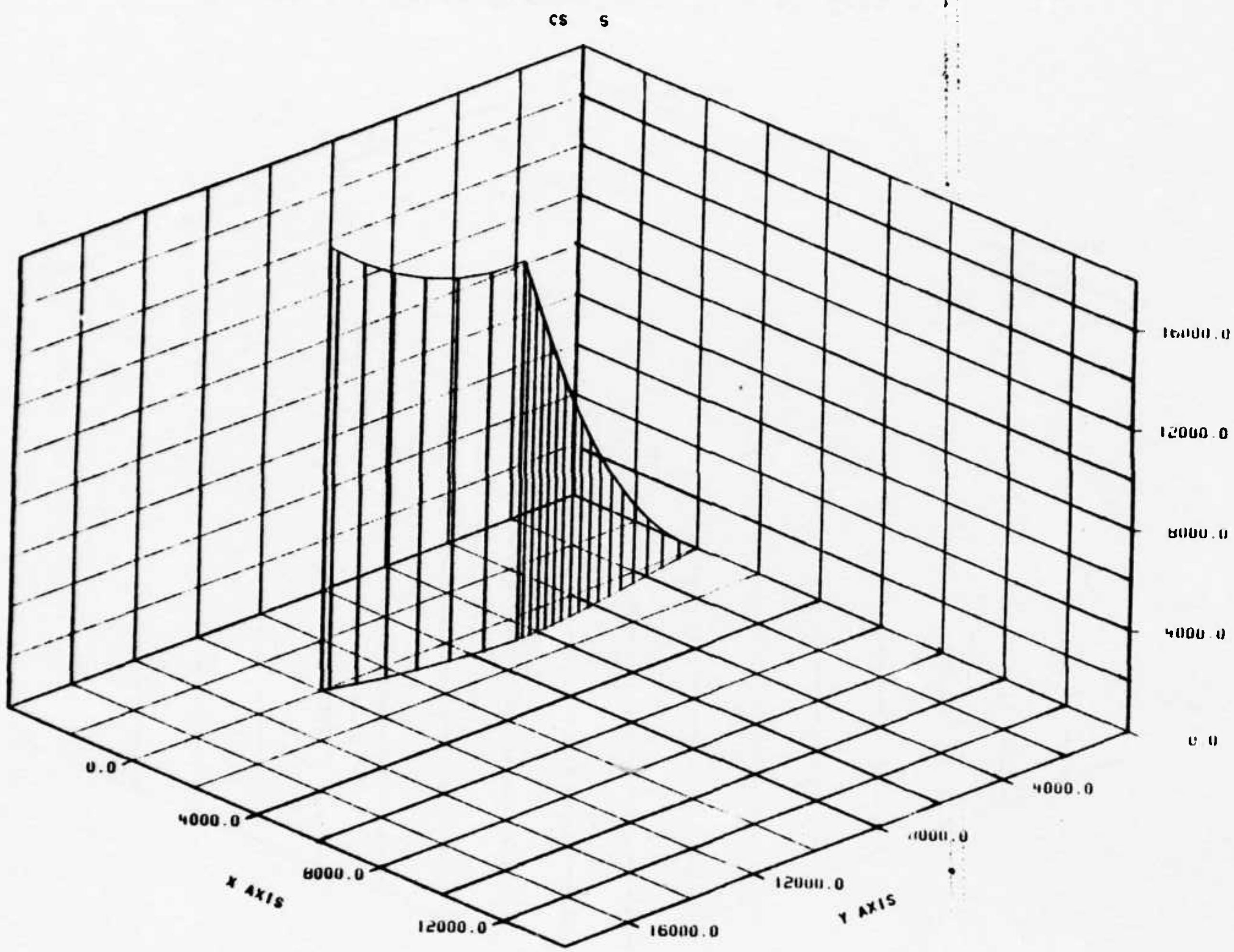


Figure 19. Three Dimensional Plot of Case 5

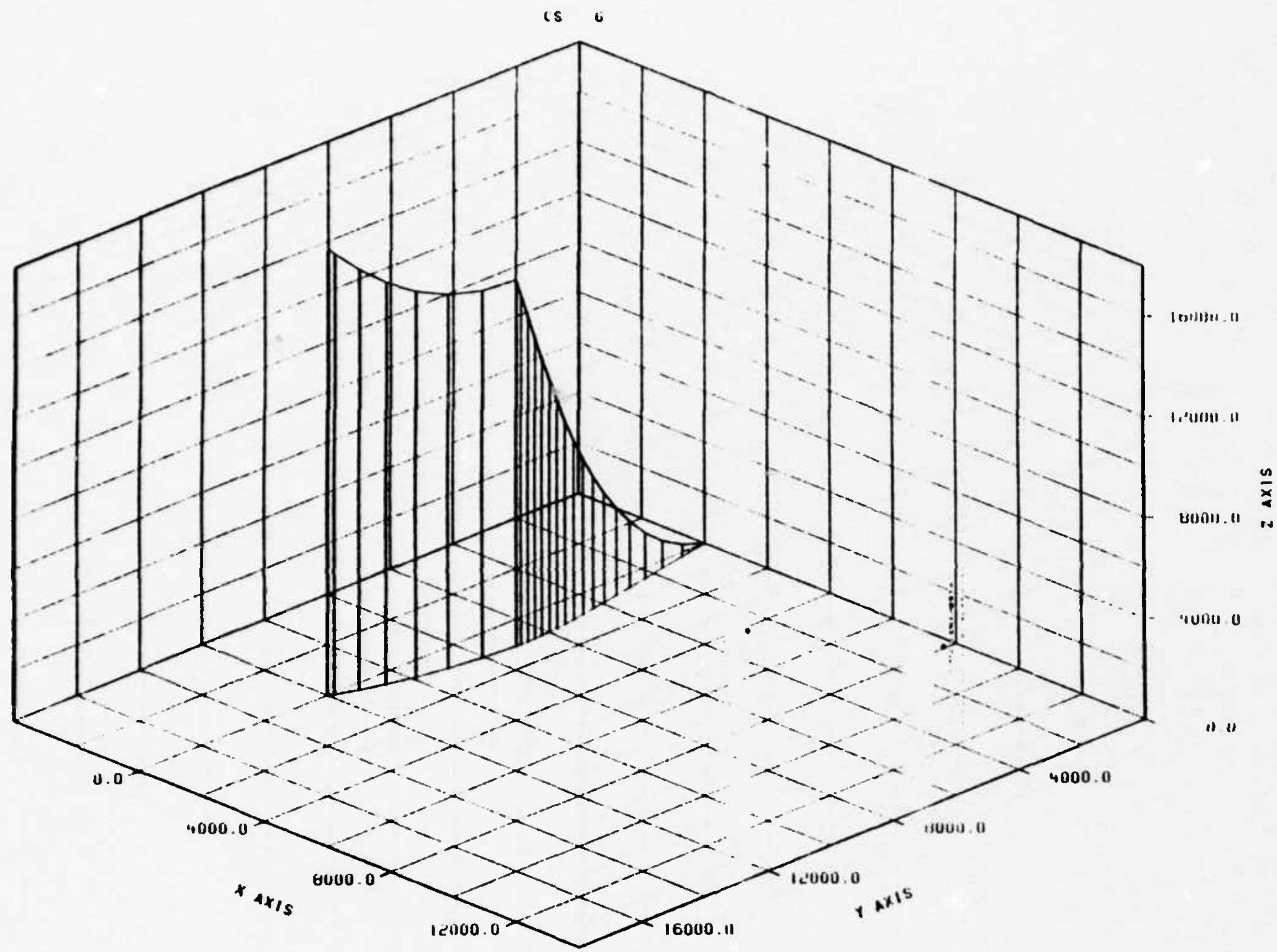


Figure 20. Three Dimensional Plot of Case 6

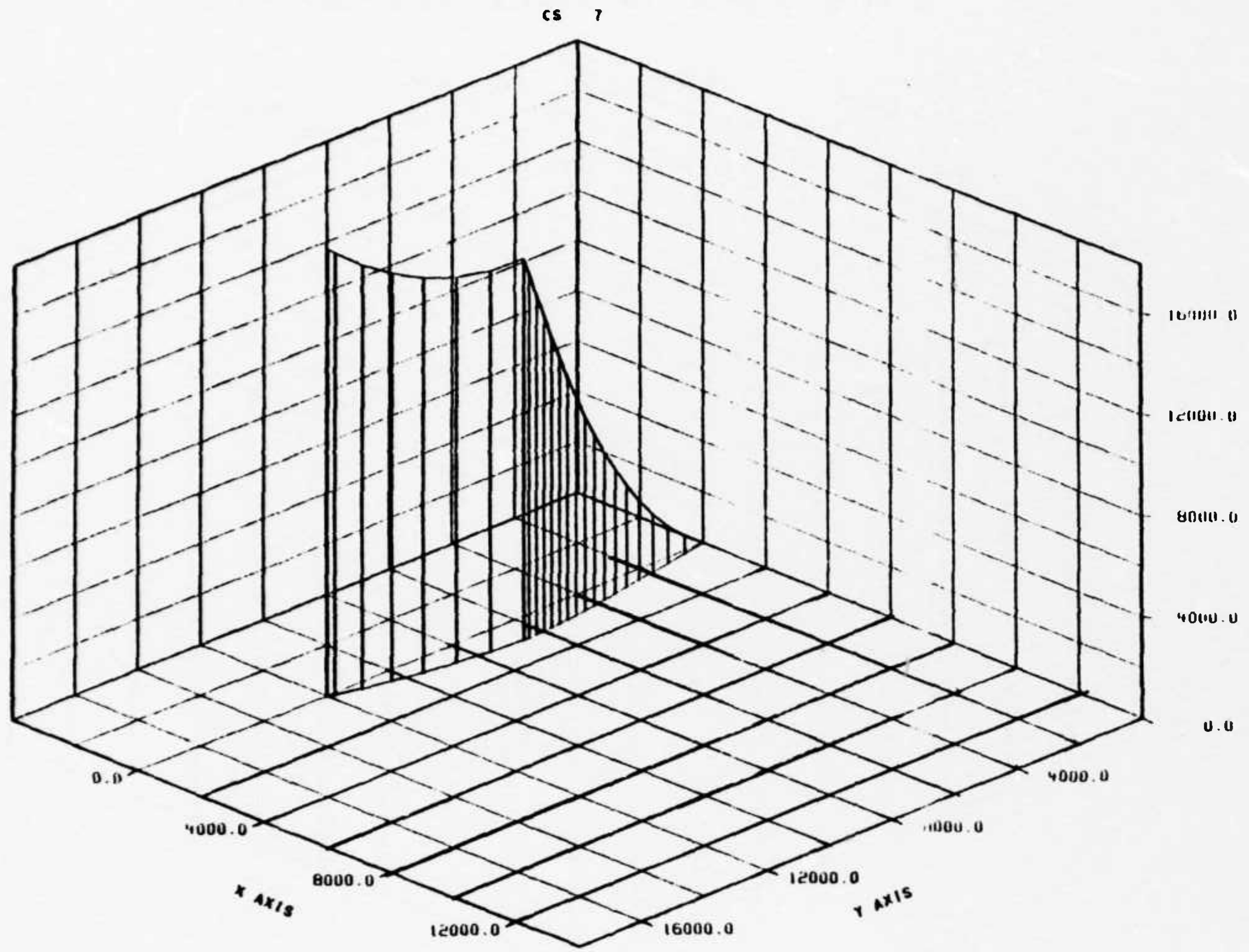


Figure 21. Three Dimensional Plot of Case 7

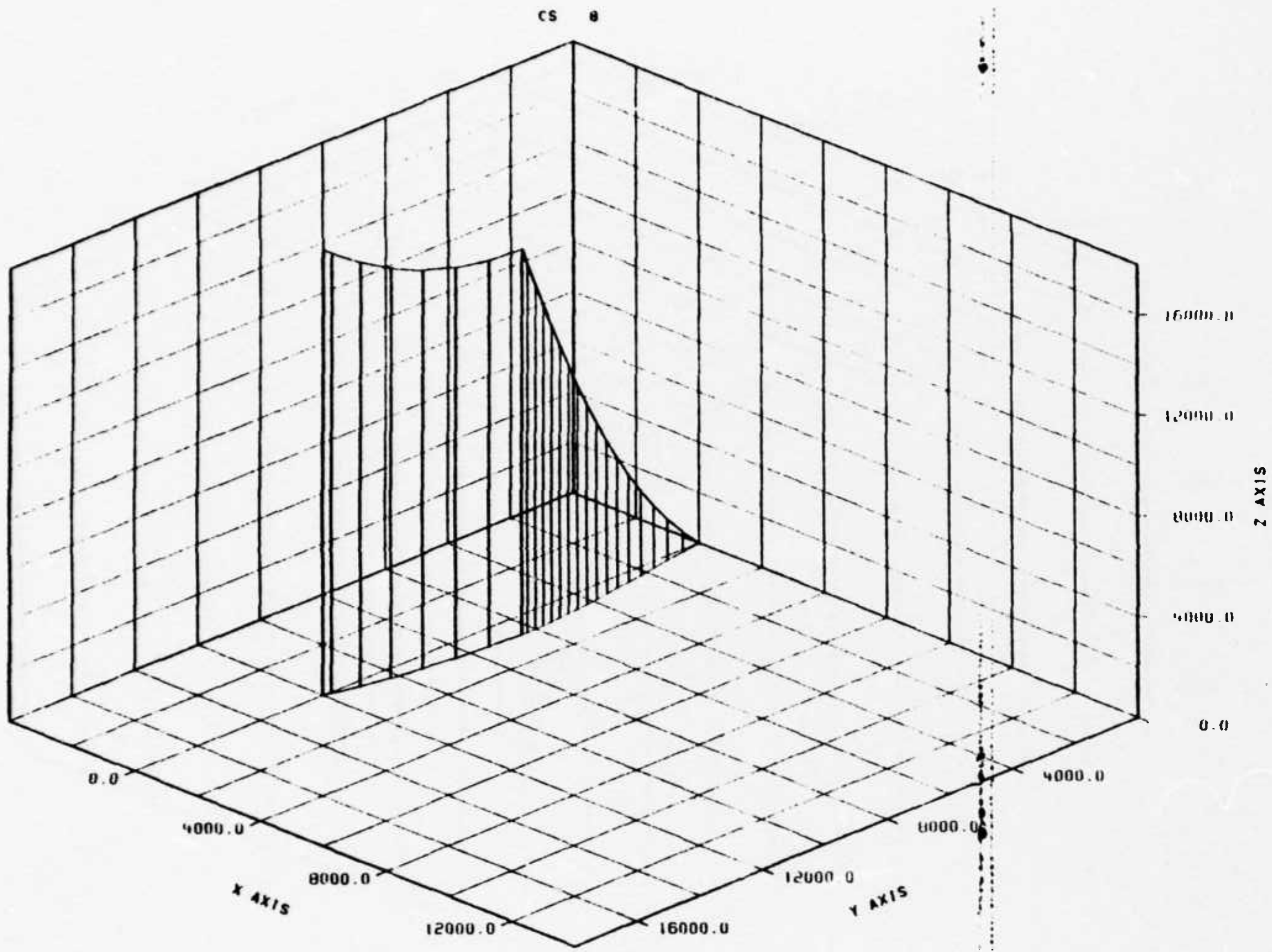


Figure 22. Three Dimensional Plot of Case 8

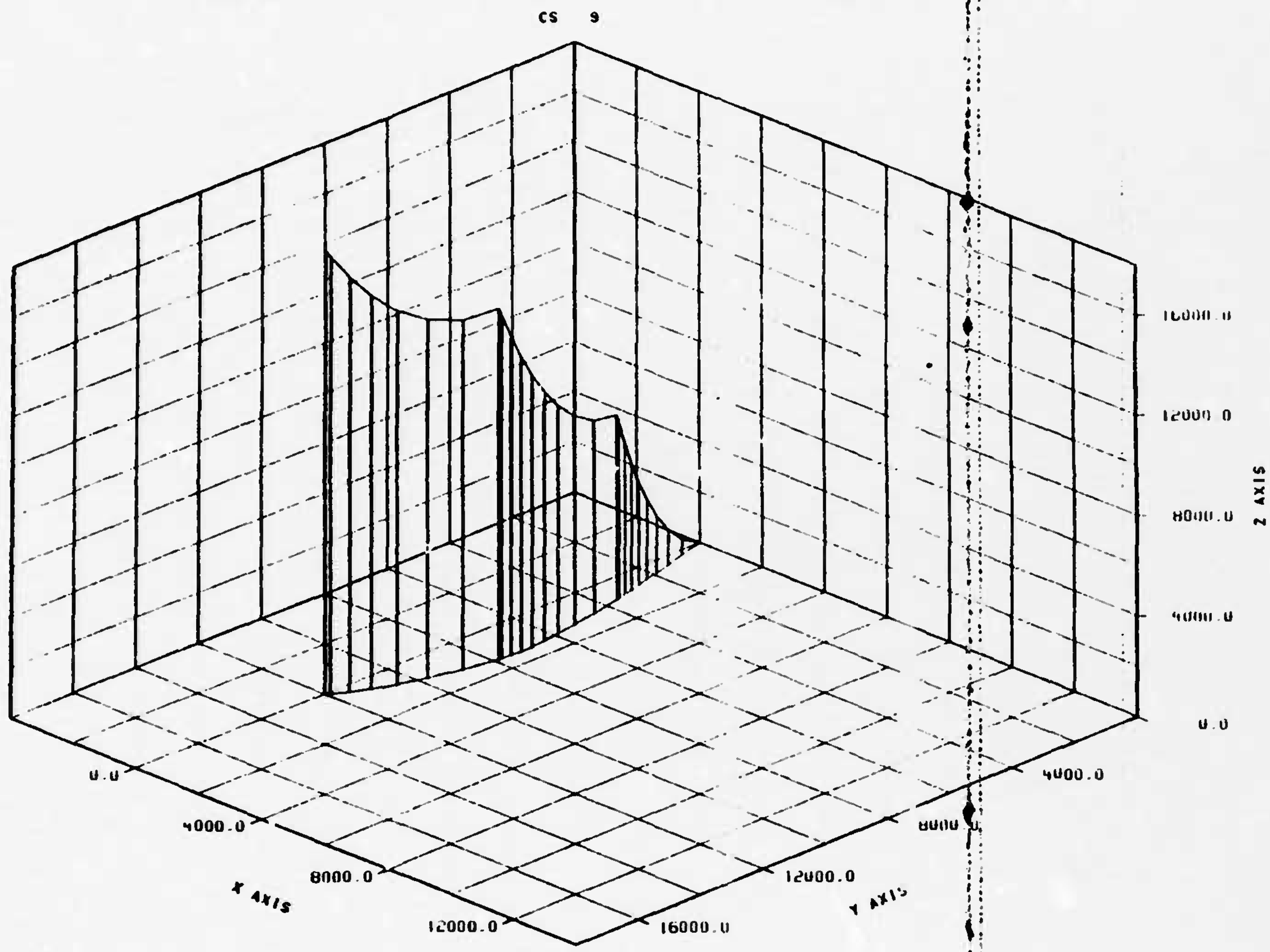


Figure 23. Three Dimensional Plot of Case 9

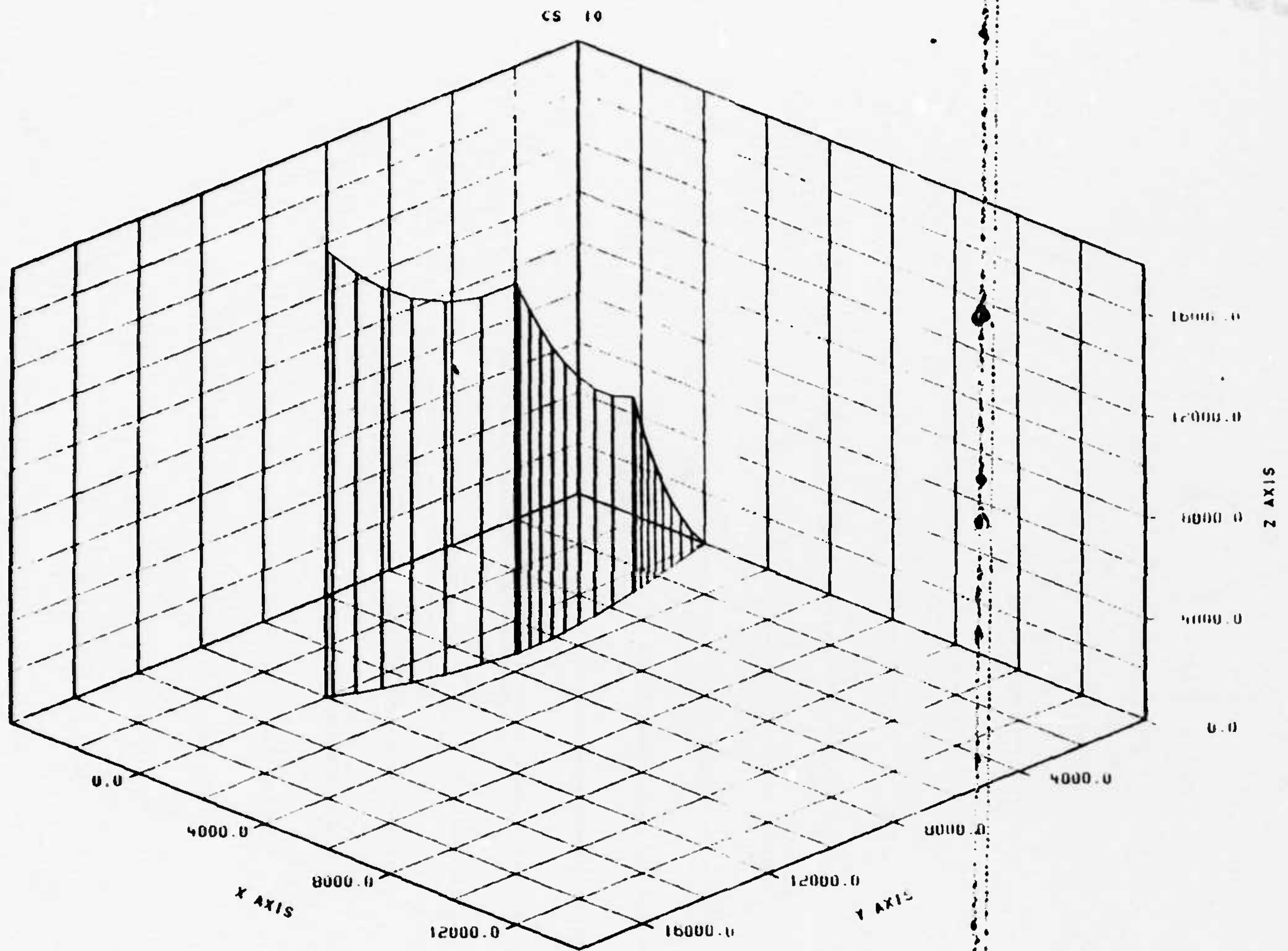


Figure 24. Three Dimensional Plot of Case 10

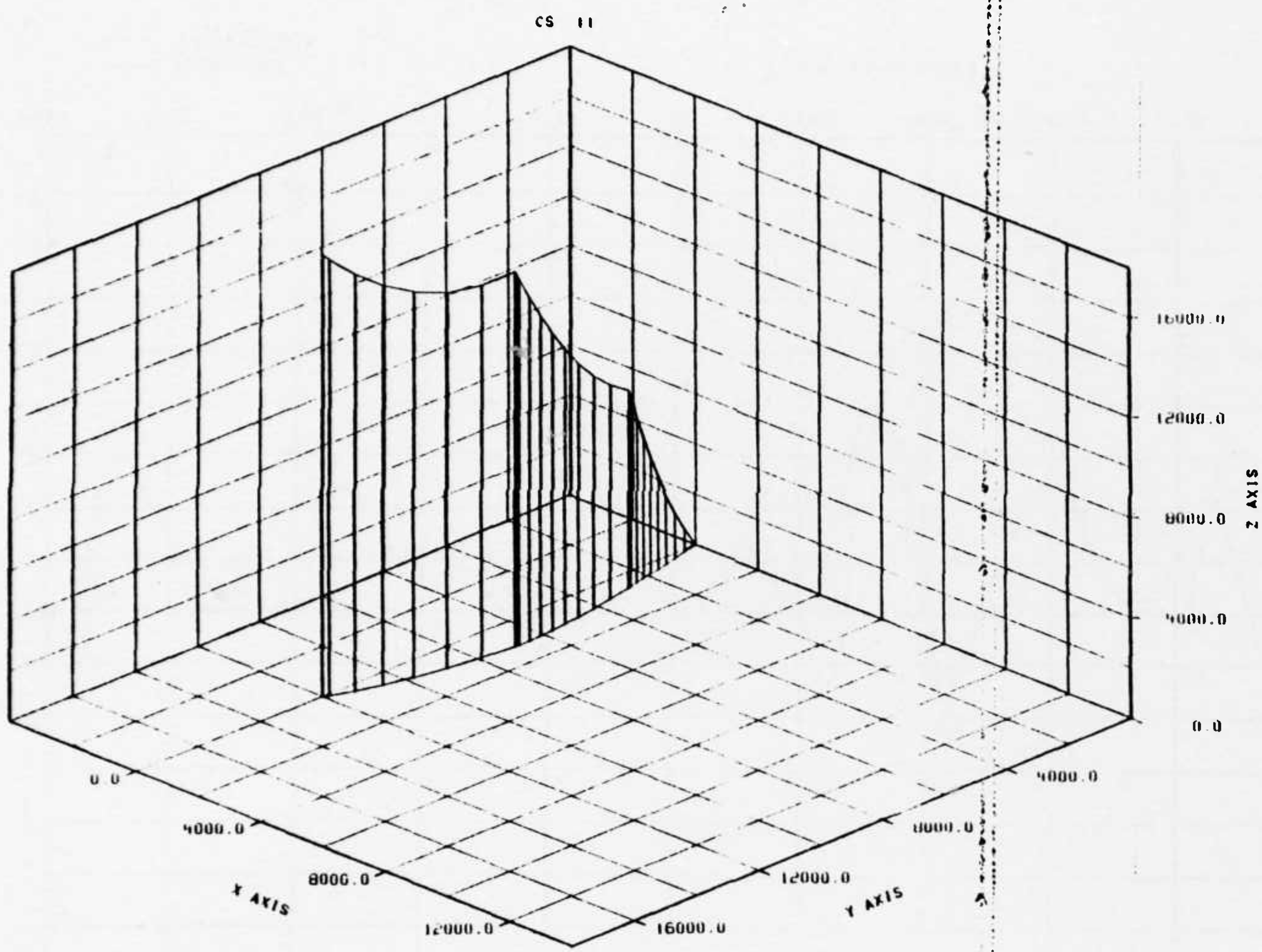


Figure 25. Three Dimensional Plot of Case 11

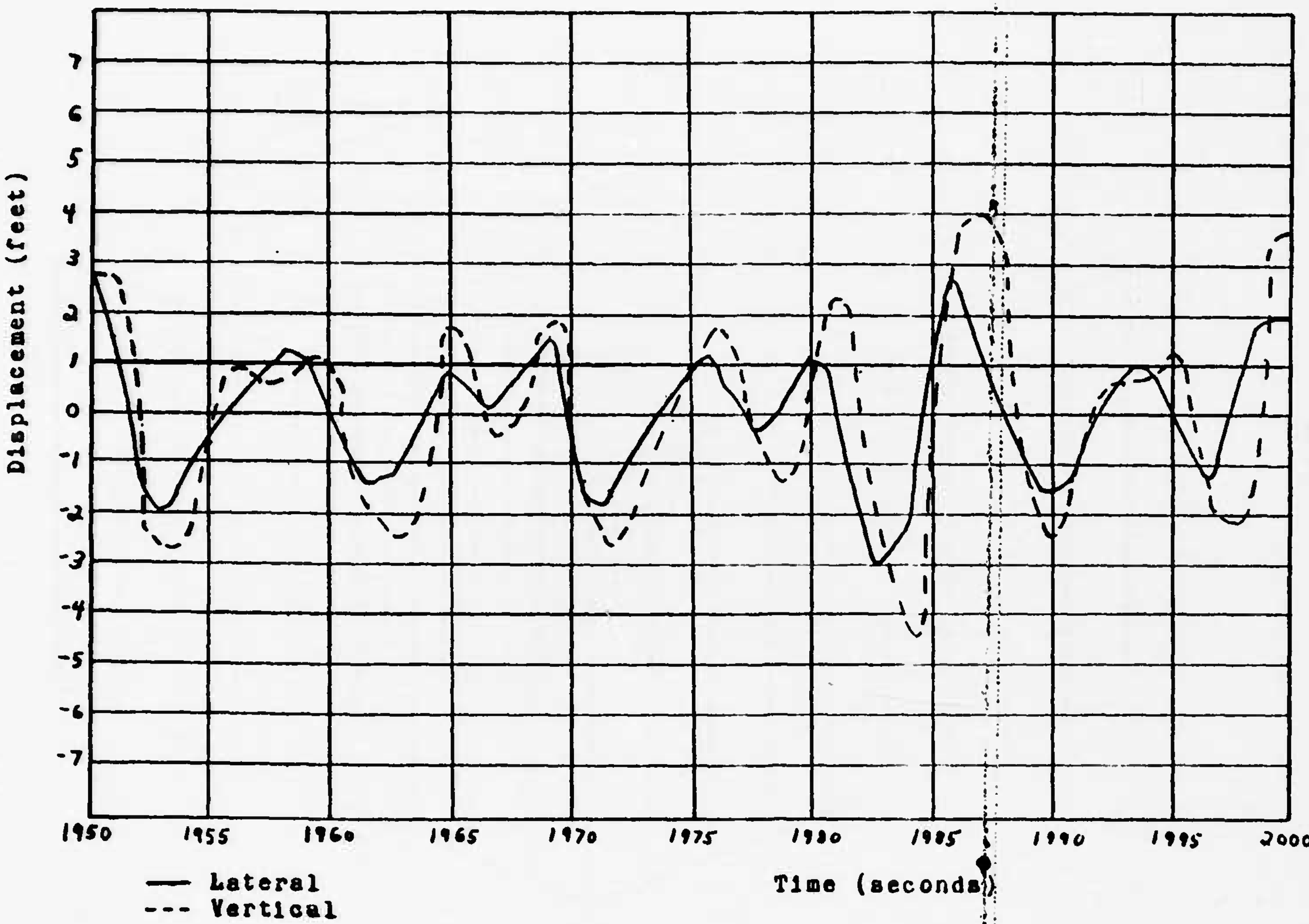


Figure 26. Displacement of Ship versus Time for Case 12

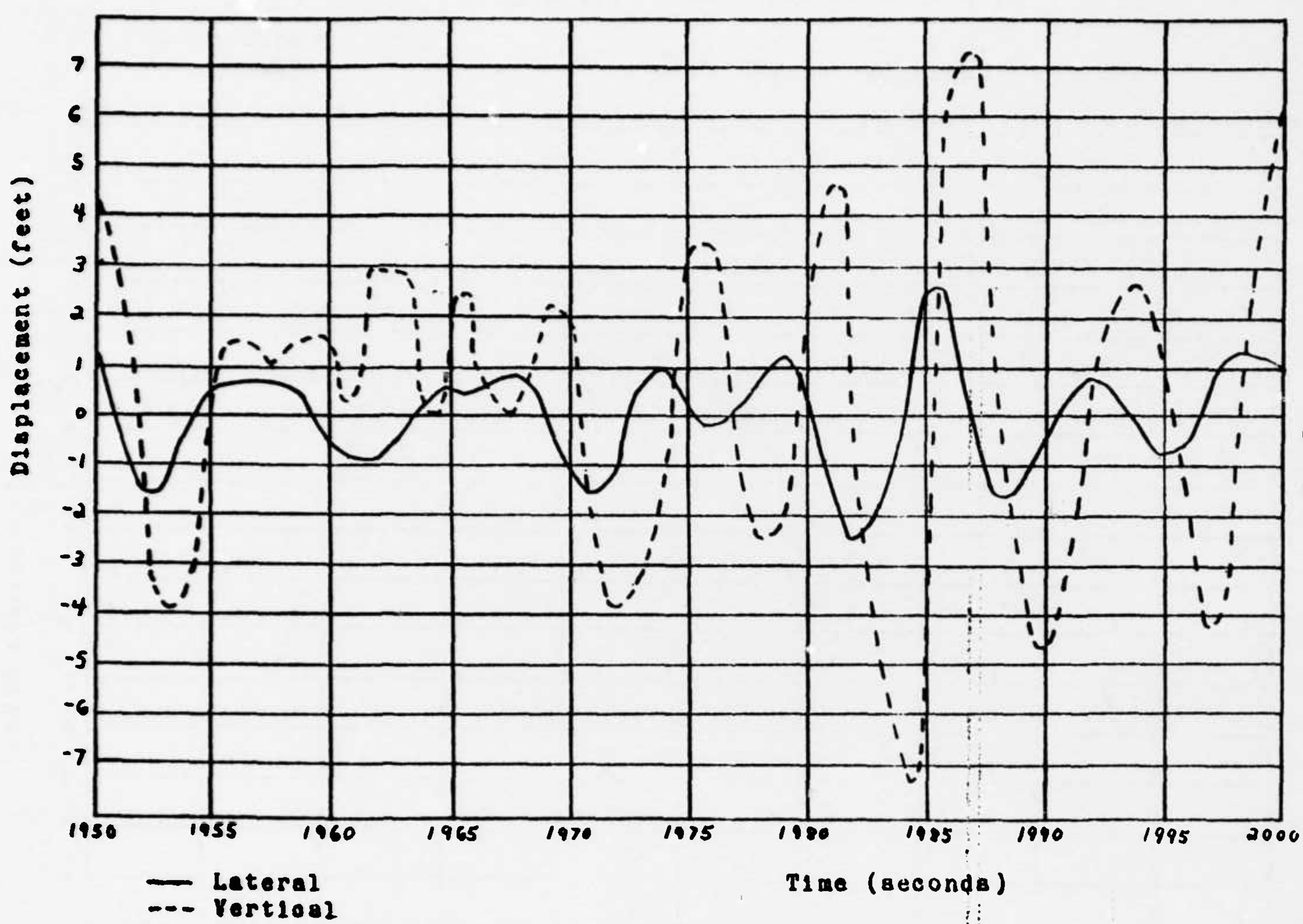


Figure 27. Displacement of Ship versus Time for Case 13

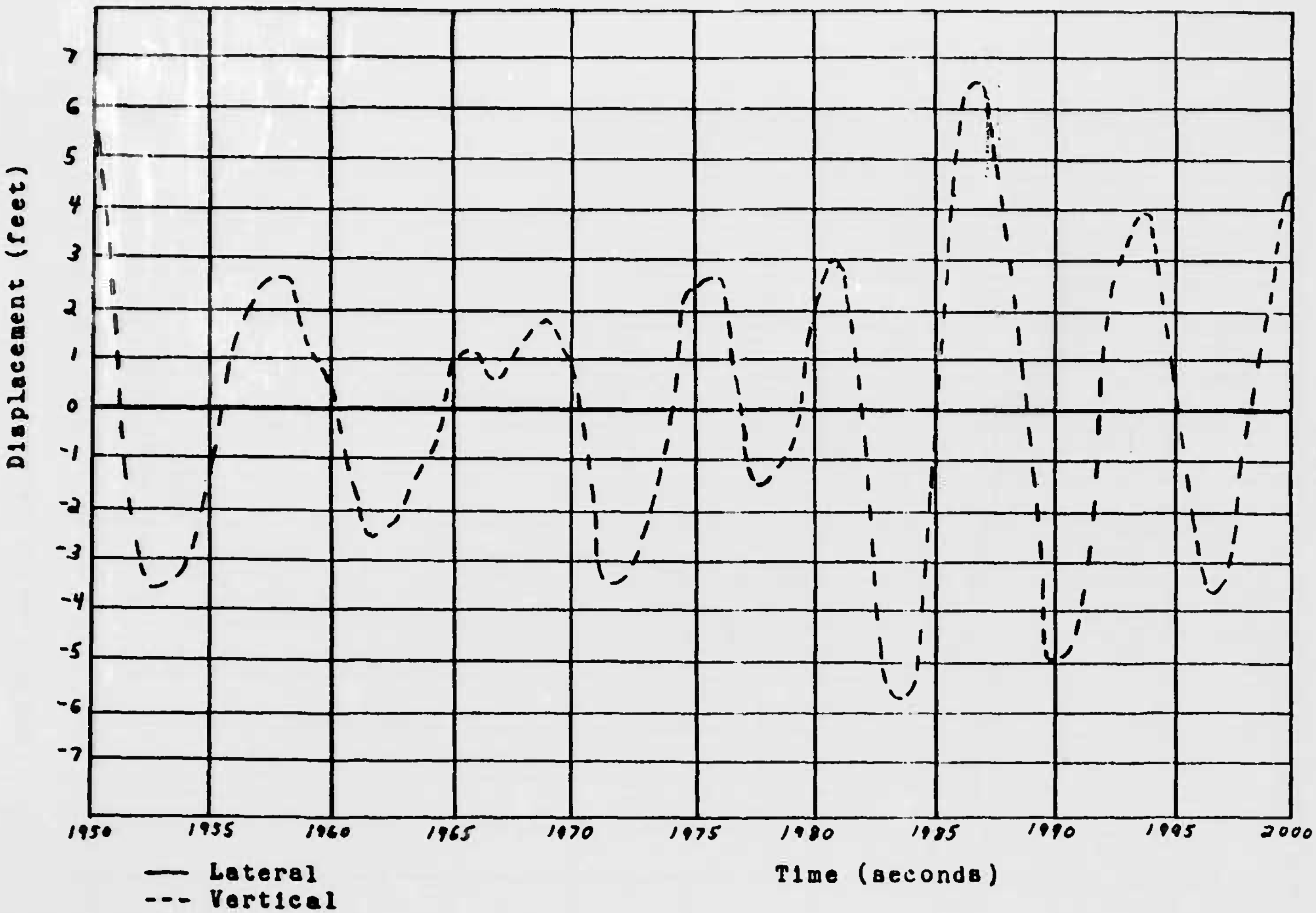


Figure 28. Displacement of Ship versus Time for Case 14

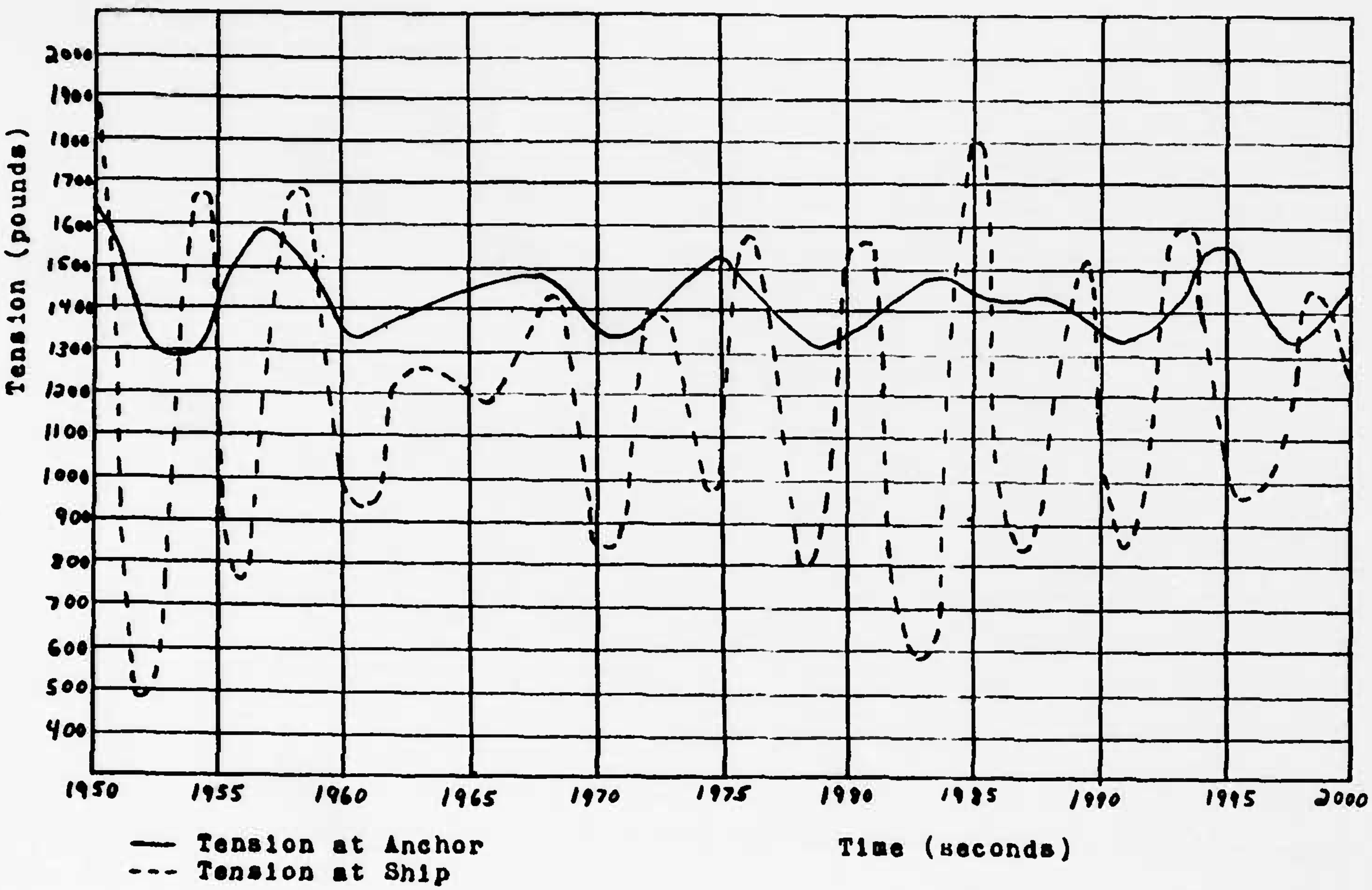


Figure 29. Tension at Anchor and Tension at Ship versus Time for Case 12

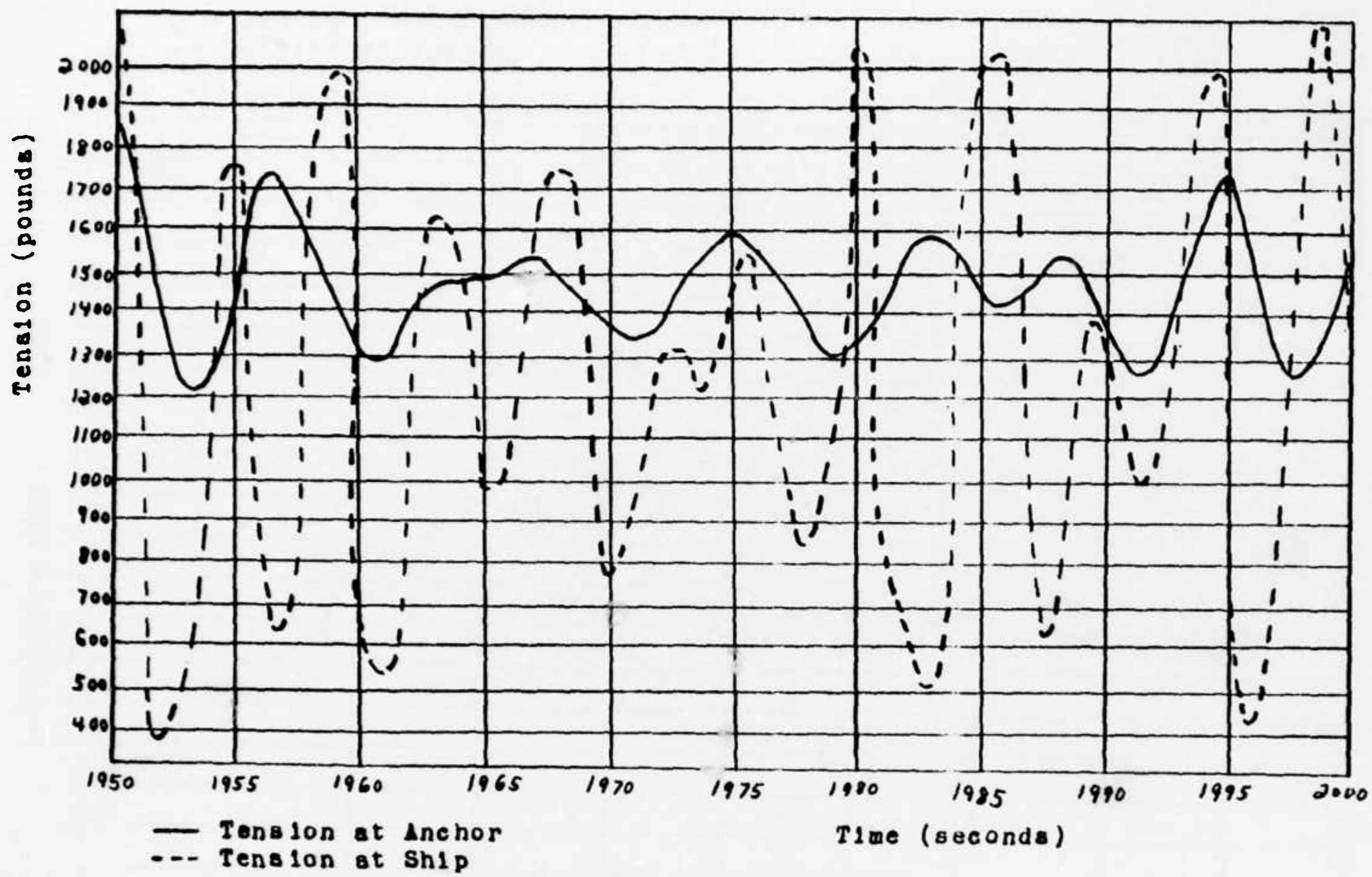


Figure 30. Tension at Anchor and Tension at Ship versus Time for Case 13

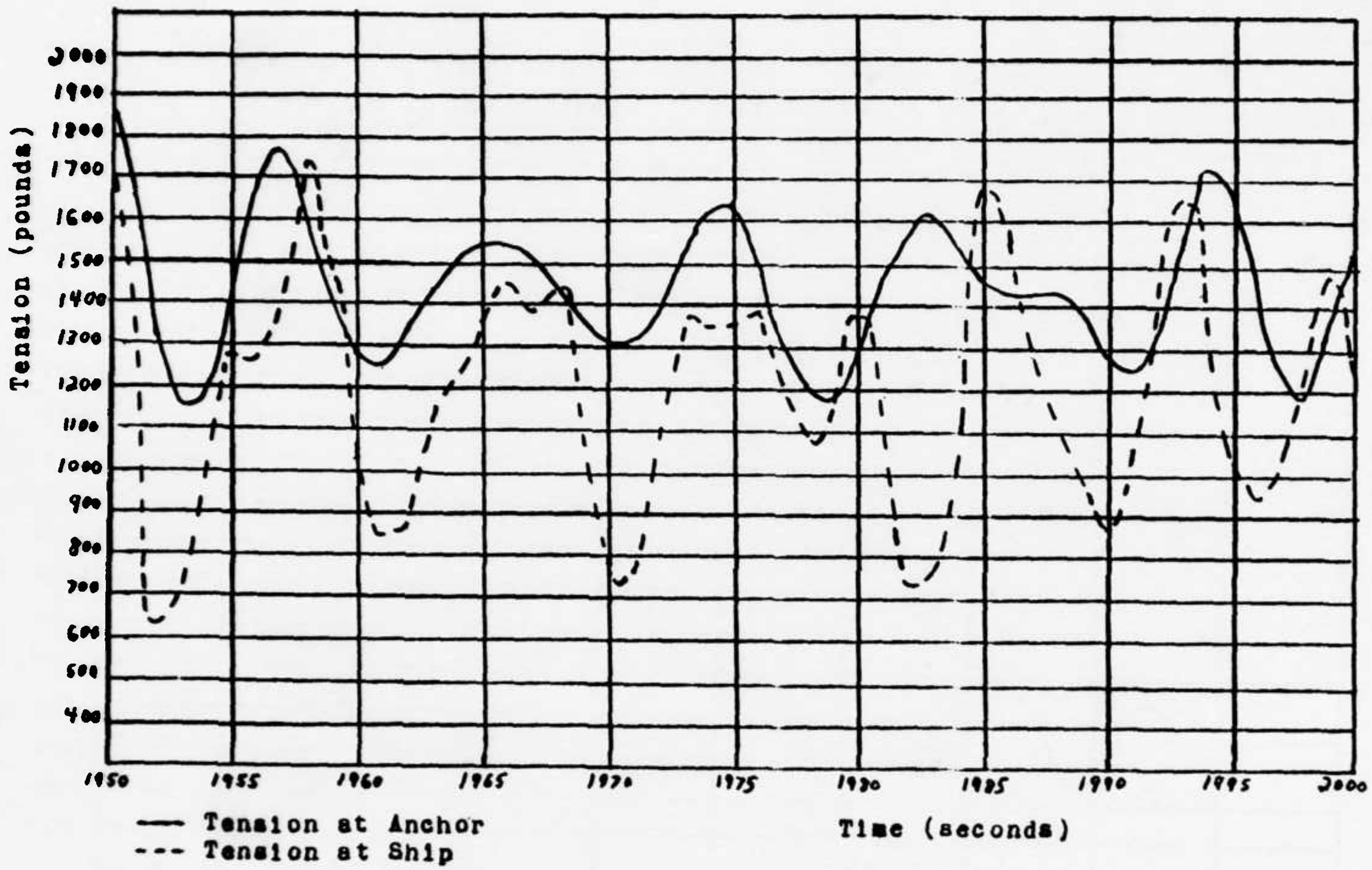
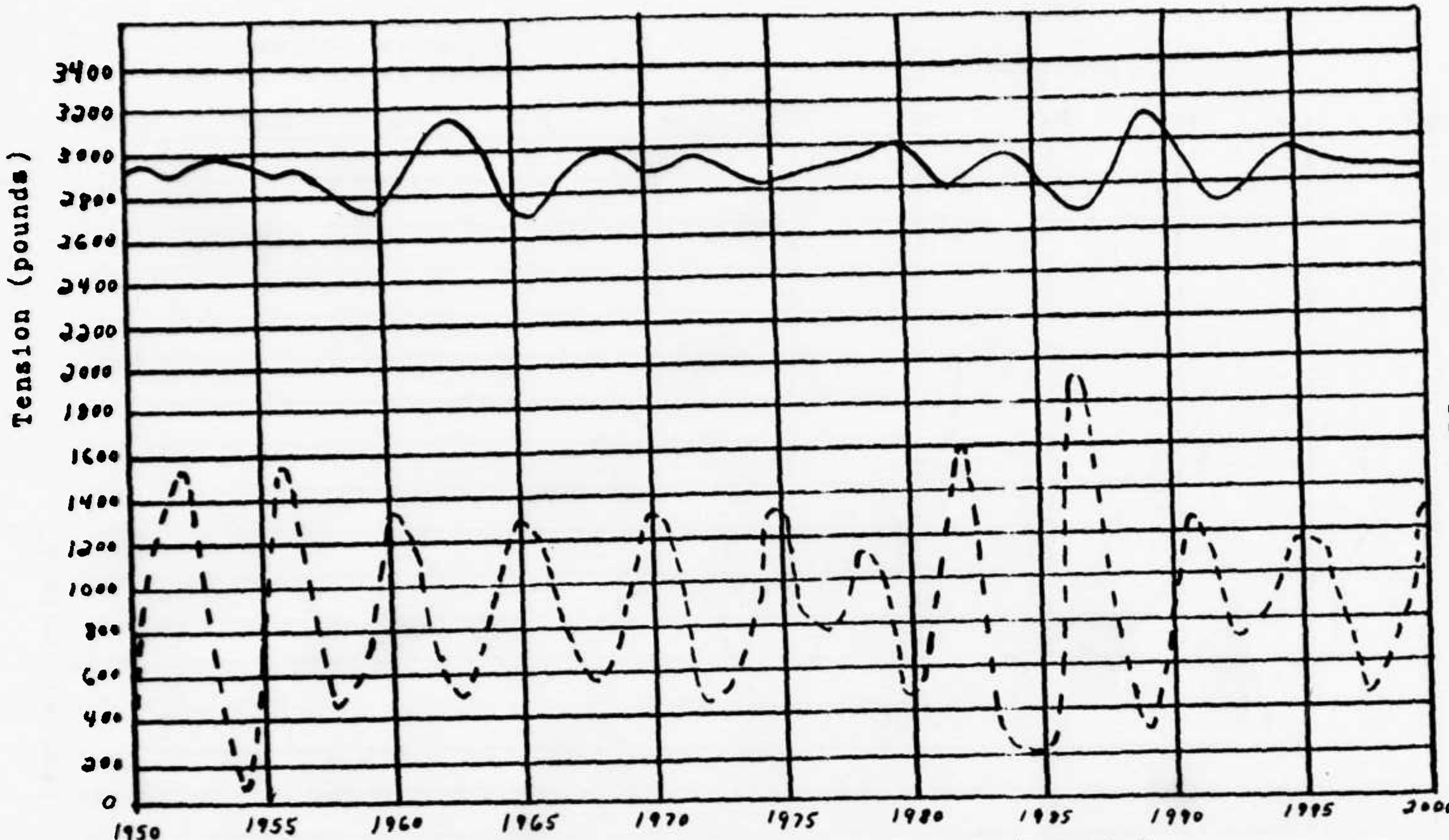


Figure 31. Tension at Anchor and Tension at Ship versus Time for Case 14



— Tension in segment 3 (below buoy)
--- Tension in segment 4 (above buoy)

Figure 32. Tension in Segment below Buoy and Tension in Segment above Buoy versus Time for Case 12

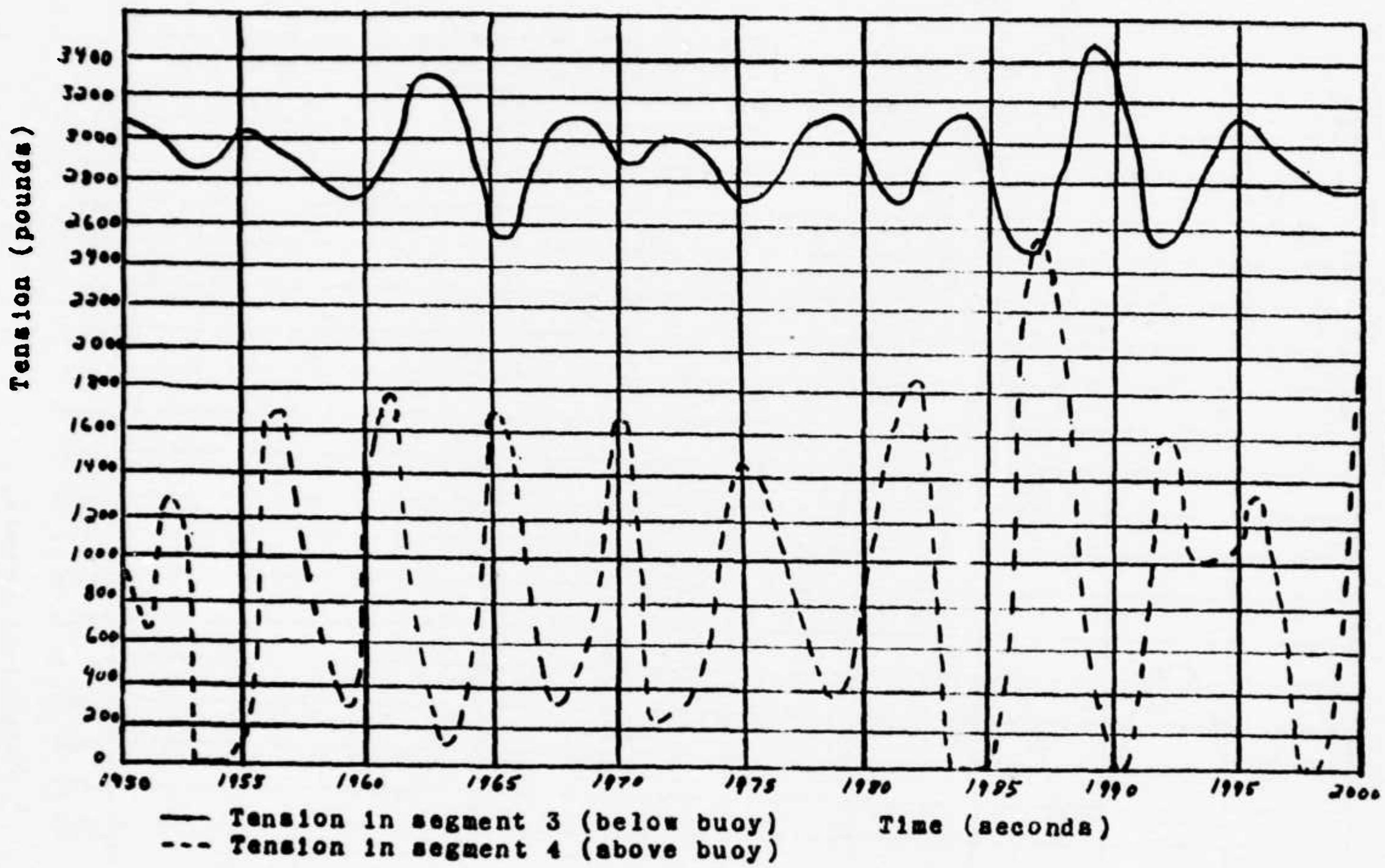


Figure 33. Tension in Segment below Buoy and Tension in Segment above Buoy versus Time for Case 113

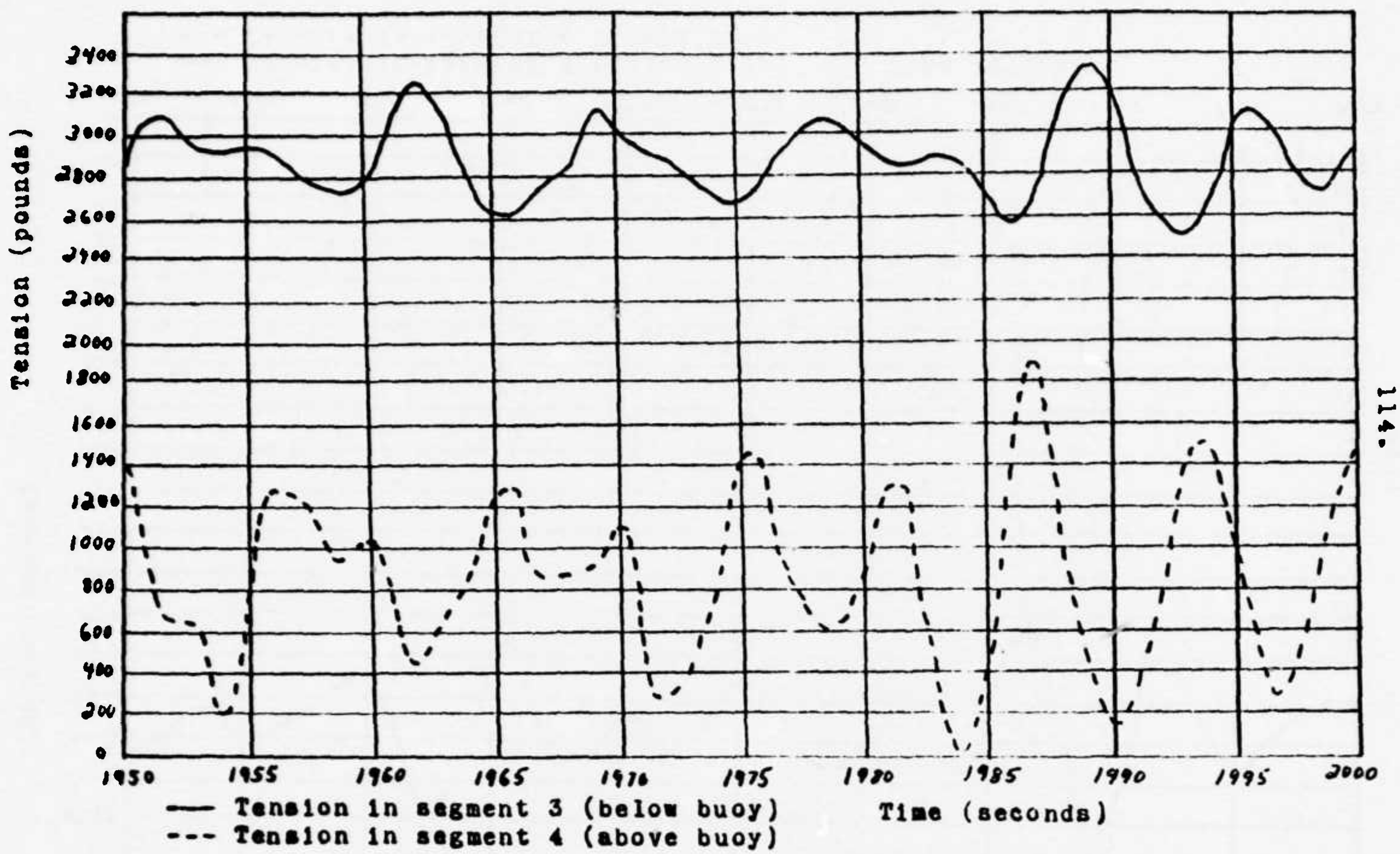


Figure 34. Tension in Segment below Buoy and Tension in Segment above Buoy versus Time for Case 14

V. SUMMARY

5.1 Conclusions

The cable-buoy-ship systems examined here were studied under a variety of conditions. First, the ship was placed at various distances from the anchor in the steady state model. Then, after selecting a "worst case" distance, the excess buoyancy of the buoy was varied. Subsequently, the effects of having two smaller buoys instead of one large one were looked at. Finally, after choosing what seemed to be the optimal system, its dynamics were examined. The ship driving the system was subjected to waves typical of a particular sea state, and its angle relative to the incident waves was varied. Tensions in the cable under simulated operating conditions were thus obtained.

The system could also be subjected to a variety of other conditions which were assumed to be constant, but which could be varied. These include the water current (magnitudes and direction), cable properties (length, diameter, and modulus of elasticity), the location of buoys on the cable, the sea state and the particular surface ship being used. This study considered these to be fixed because they were either previously specified (the cable properties or the ship) or a "worst case" condition (the sea state or

water currents).

The models employed in this study have shown that the wave-induced motions of the ship can be sufficiently decoupled from those of the cable such that cable tensions throughout the system are acceptable. Thus, in this study, a system was designed in which all the initial requirements have been satisfied.

5.2 Suggestions for Further Study

Further research in the area of cable-buoy-ship systems should include investigation of the effects of additional buoys spaced along the cable. While the present model can account for a maximum of only two buoys, it would be relatively straightforward to modify the program so that systems consisting of many buoys could be modeled.

This would be accomplished by integrating along the cable up to each successive buoy. At each buoy, as before, the force and moment equilibrium equations would be solved. Integration up the cable would then take place again. This process would be repeated until the ship was reached. (It should be noted that the program has been successfully modified to account for a specific system consisting of four buoys. These results will be described in a forthcoming report of the Naval Underwater Systems Center.)

Another possible useful option would be the capability of specifying one buoy as a surface buoy. This was seriously considered during this study, but the results were not conclusive. When the iterative process used for finding the steady state tension at the anchor (see section 2.3) was tried, difficulties were encountered in obtaining convergence. The reason for this was that, when the tension at the anchor was "corrected" by only a few pounds, the draft of the surface buoy would change by a few feet, resulting in a significant change in the buoyancy force at the buoy. It was realized, then, that the iteration process of section 2.3 could not be used in its present form for the entire system. Instead, the following scheme, which is described in detail below is proposed to obtain the steady state tensions:

Let the problem be divided into two distinct parts; the first part looks at the cable from the anchor up to, but not including, the surface buoy. The second examines the surface buoy and the tether to the ship.

The procedure for finding the tensions and positions of the cable for the first section of cable mentioned above is identical to that used in previous sections. There is, however, one slight change: the model treats the surface buoy as if it were the ship. The horizontal distance from

the anchor to the ship, G (see figure 8), becomes the horizontal distance from the anchor to the surface buoy. The water depth, H, is decreased by an amount which is 0.6 times the buoy diameter. (This means that the buoy is initially assumed to have a draft which is 60 percent of its diameter.) When the desired location of the surface buoy is finally attained through the use of the iteration process described in section 2.3, the surface buoy and its tether to the ship may be examined.

The tension in the cable from the anchor at the surface buoy, which was calculated using the above procedure, is assumed to be constant. The general idea now is to adjust the draft of the surface buoy such that the ship will be on the ocean surface. (Since the cable to the anchor is assumed to be very long, on the order of several miles long, a change of a few feet at the surface buoy in the vertical direction should not be significant with respect to cable tensions and positions between the anchor and surface buoy.)

The initial "guess" for the buoy draft is that it is 0.6 times the buoy diameter. Using this value, equilibrium equations may be written and solved at the buoy, and the cable tether is subsequently integrated to the ship. The z (vertical) coordinate of the ship, z_{SH}, is then compared to the known water depth, H. If the difference between these

two values is less than some prescribed value ε, then this iteration has produced the final results. Otherwise, the following correction is applied to the next iteration:

$$H_{D_k} = H_{D_{(k-1)}} + \frac{z_{SH_k} - H}{(4)(k+19)^2}$$

where

H_{D_k}	=	the buoy draft of the k'th iteration
$H_{D(k-1)}$	=	the buoy draft of the (k-1)'th iteration
z_{SH_k}	=	the z coordinate of the ship of the (k-1)'th iteration
H	=	the water depth
k	=	the iteration number

Using this "corrected" value for the buoy draft, equilibrium requirements are satisfied at the buoy, and the cable again is integrated to the ship. This process is repeated until, as already stated, the error becomes sufficiently small.

The scheme described above was incorporated into a model, and successful convergence was obtained. (The iterations were repeated until the ship was found to be located on the surface of the water.) Although this method has been

shown to be convergent, further examination of the assumptions must be made before the results can be taken to be accurate.

As is the case with most computer models of physical systems, a comparison of the results obtained from the simulation with experimental data should be made. It would thus be useful to compare the results predicted by this study with those of an actual system operating at sea in order to validate the model.

In addition, certain parameters and constants of the program could be given more accuracy. These could include the drag coefficients, hydrodynamic mass coefficients, etc. Modifications could be made such that cable strumming would be allowed to occur if it were appropriate for a certain system. (Cable strumming is neglected entirely in this study)

Useful information could most definitely be obtained by comparing the amplitudes and phases of the tension versus time plots. This would include examining the tensions at identical segments of the cable for various ship headings and comparing the tensions in various segments for the same ship heading. A detailed analysis of this type would require the use of sophisticated statistical methods.

An interesting extension of this study would be to not assume that the anchor is fixed; that is, the anchor would

be taken to be a certain weight. If the tension components at the anchor exceeded certain limits, then two things could happen. First, the anchor would be lifted off the bottom if the limit for the vertical component were exceeded. Second, the andhor would be dragged along the ocean floor if the limit for the horizontal tension component were exceeded.

Finally, ways could be found to reduce the running time of the program. For example, the step size in time, b, (see section 3.4) could be examined to see how large it can get before inaccurancies and numerical instability occur. A reduction in time would realize significant savings in cost for the user.

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Appendix A

THE FOURTH ORDER RUNGE-KUTTA METHOD

Consider the initial-value problem:

$$\frac{dy}{dx} = y' = F(x, y) \qquad \text{(A1)}$$

$$y(x_0) = y_0 \qquad \text{(A2)}$$

The increment Δy for advancing the dependent variable when the independent variable is advanced by h is given by

$$\Delta y = \frac{1}{6}\left(k_1 + 2k_2 + 2k_3 + k_4\right) + O\left(h^5\right) \qquad \text{(A3)}$$

where

$$k_1 = h\,F(x_n, y_n) \qquad \text{(A4a)}$$

$$k_2 = h\,F\left(x_n + \frac{1}{2}h,\ y_n + \frac{1}{2}k_1\right) \qquad \text{(A4b)}$$

$$k_3 = h\,F\left(x_n + \frac{1}{2}h,\ y_n + \frac{1}{2}k_2\right) \qquad \text{(A4c)}$$

$$k_4 = h\,F\left(x_n + h,\ y_n + k_3\right) \qquad \text{(A4d)}$$

The values at (x_{n+1}, y_{n+1}) are then:

$$x_{n+1} = x_n + h \tag{A5a}$$

$$y_{n+1} = y_n + \Delta y \tag{A5b}$$

All intervals are computed in the same manner, using for the initial values the values at the beginning of each interval. The method does not need any special formulas to get the solution started, and it is well suited to computational form.

Appendix B

SOLUTION OF BUOY EQUATIONS

B.1 Equilibrium Equations

Equations (12) are:

$$-(T_{BE})_x + (D_F)_x - (T_{BD})(\sin\theta_{BD})(\cos\phi_{BD}) = 0 \tag{B1a}$$

$$-(T_{BE})_y + (D_F)_y + (T_{BD})(\cos\theta_{BD})(\cos\phi_{BD}) = 0 \tag{B1b}$$

$$-(T_{BE})_z + (B) + (T_{BD})(\sin\phi_{BD}) = 0 \tag{B1c}$$

Letting

$$AEX = \left[-(T_{BE})_x + (D_F)_x\right] \tag{B2a}$$

$$AEY = \left[(T_{BE})_y - (D_F)_y\right] \tag{B2b}$$

$$AEZ = \left[(T_{BE})_z - (B)\right] \tag{B2c}$$

the above equations may be rewritten as:

$$T_{BD} \sin \theta_{BD} \cos \phi_{BD} = AEX \tag{B3a}$$

$$T_{BD} \cos \theta_{BD} \cos \phi_{BD} = AEY \tag{B3b}$$

$$T_{BD} \sin \phi_{BD} = AEZ \tag{B3c}$$

Dividing equation (B3c) by (B3a) gives:

$$\frac{\tan \phi_{BD}}{\sin \theta_{BD}} = \frac{AEZ}{AEX} \tag{B4}$$

Dividing equation (B3c) by (B3b) yields:

$$\frac{\tan \phi_{BD}}{\cos \theta_{BD}} = \frac{AEZ}{AEY} \tag{B5}$$

Rewriting equation (B4):

$$\tan \phi_{BD} = \frac{AEZ}{AEX} \sin \theta_{BD} \tag{B6}$$

Putting equation (B6) into (B5):

$$\frac{\sin \theta_{BD}}{\cos \theta_{BD}} \cdot \frac{AEZ}{AEX} = \frac{AEZ}{AEY} \tag{B7}$$

or

$$\tan \theta_{BD} = \frac{AEX}{AEY} \tag{B8}$$

which implies

$$\theta_{BD} = \tan^{-1}\left(\frac{AEX}{AEY} \right) \tag{B9}$$

Equation (B6) may now be solved for

$$\phi_{BD} = \tan^{-1} \left[\left(\frac{AEZ}{AEX} \right) \sin \theta_{BD} \right] \tag{B10}$$

or, from equation (B9), letting

$$AEX = (AEY)(\tan \theta_{BD}) \tag{B11}$$

equation (B10) may be rewritten as:

$$\phi_{BD} = \tan^{-1} \left[\left(\frac{AEZ}{AEY} \right) (\cos \theta_{BD}) \right] \tag{B12}$$

Finally, T_{BD} may be found by rewriting equation (B3c):

$$T_{BD} = \frac{AEZ}{\sin \phi_{BD}} \tag{B13}$$

If ABY is calculated to be zero, then $\Theta_{BD} = 90^\circ$ if ABX is positive and $\Theta_{BD} = -90^\circ$ if ABX is negative. Similarly if ABY is calculated to be zero, then $\phi_{BD} = 90^\circ$ if ABZ is positive and $\phi_{BD} = -90^\circ$ if ABZ is negative.

Finally, if ϕ_{BD} is calculated to be zero (which is not expected), the program will automatically be stopped as it cannot evaluate equation (B13).

B.2 Moment Equations

Equations (16a), (16b), and (17) are:

$$(B)\left(\frac{y_{DB}}{2}\right) + (T_{BD})_z (y_{DB}) - (D_F)_y \left(\frac{z_{DB}}{2}\right) - (T_{BD})_y (z_{DB}) = 0 \qquad \text{(B14a)}$$

$$(D_F)_x \left(\frac{z_{DB}}{2}\right) + (T_{BD})_x (z_{DB}) - (B)\left(\frac{x_{DB}}{2}\right) - (T_{BD})_z (x_{DB}) = 0 \qquad \text{(B14b)}$$

$$(2R_s)^2 = (x_{DB})^2 + (y_{DB})^2 + (z_{DB})^2 \qquad \text{(B14c)}$$

where, from equations (15):

$$x_{DB} = x_D - x_E \qquad \text{(B15a)}$$

$$y_{DB} = y_D - y_E \qquad \text{(B15b)}$$

$$z_{DB} = z_D - z_E \qquad \text{(B15c)}$$

Combining like terms of equations (B14) gives:

$$\left[\left(\frac{B}{2}\right) + (T_{BD})_z\right](y_{DB}) - \left[\left(\frac{(D_R)_y}{2}\right) + (T_{BD})_y\right](z_{DB}) = 0 \quad \text{(B16a)}$$

$$\left[\left(\frac{(D_R)_x}{2}\right) + (T_{BD})_x\right](z_{DB}) - \left[\left(\frac{B}{2}\right) + (T_{BD})_z\right](x_{DB}) = 0 \quad \text{(B16b)}$$

$$(2R_S)^2 = (x_{DB})^2 + (y_{DB})^2 + (z_{DB})^2 \quad \text{(B16c)}$$

Let

$$C_1 = \left[\left(\frac{B}{2}\right) + (T_{BD})_z\right] \quad \text{(B17a)}$$

$$C_2 = \left[\left(\frac{(D_R)_y}{2}\right) + (T_{BD})_y\right] \quad \text{(B17b)}$$

$$C_3 = \left[\left(\frac{(D_R)_x}{2}\right) + (T_{BD})_x\right] \quad \text{(B17c)}$$

$$D_S = 2R_S \quad \text{(B17d)}$$

Then, substitution of the above expressions into equations (B16) yields:

$$(c_1)(y_{DB}) - (c_2)(z_{DB}) = 0 \tag{B18a}$$

$$(c_3)(z_{DB}) - (c_1)(x_{DB}) = 0 \tag{B18b}$$

$$(D_s)^2 = (x_{DB})^2 + (y_{DB})^2 + (z_{DB})^2 \tag{B18c}$$

Solving for y_{DB} and x_{DB} in equations (B18a) and (B18b) respectively gives:

$$y_{DB} = \left(\frac{c_2}{c_1}\right)(z_{DB}) \tag{B19a}$$

$$x_{DB} = \left(\frac{c_3}{c_1}\right)(z_{DB}) \tag{B19b}$$

(c_1 is never expected to be equal to zero.)

Substitution of the above expressions into equation (B18c) gives:

$$(D_s)^2 = \left[\left(\frac{c_2}{c_1}\right)^2 + \left(\frac{c_3}{c_1}\right)^2 + 1\right](z_{DB})^2 \tag{B19c}$$

This equation may be solved as follows:

$$z_{DB} = \frac{D_s}{\sqrt{\left(\frac{C_2}{C_1}\right)^2 + \left(\frac{C_2}{C_1}\right)^2 + 1}} \tag{B20}$$

The solution for the unknown coordinates, then, may be taken from a rearrangement of equations (B15):

$$x_D = x_E + x_{DB} \tag{B21a}$$

$$y_D = y_E + y_{DB} \tag{B21b}$$

$$z_D = z_E + z_{DB} \tag{B21c}$$

where all the terms are as previously defined.

Appendix C

COMPUTER PROGRAM DESCRIPTION

C.1 Current Profile

The program computes the current velocity as a function of depth. The current direction is assumed to be constant and the current velocity vector at any depth is contained in a horizontal plane. Assume that the current, V_c, has a velocity of c_x knots at the surface, decreases exponentially to c_y knots at a depth of D feet, and varies linearly at greater depths to c_B knots at the bottom, at a water depth of H feet:

$$v_c = c_x e^{-(H-z)(c_z)} \qquad \left(H \geq z \geq (H-D)\right) \tag{C1a}$$

where

$$c_z = \frac{\ln\left(\frac{c_x}{c_y}\right)}{D} \tag{C1b}$$

$$v_c = c_B + \left(\frac{z}{H-D}\right)\left(c_y - c_B\right) \qquad \left((H-D) \geq z \geq 0\right) \tag{C2}$$

Figure C-1 shows this profile:

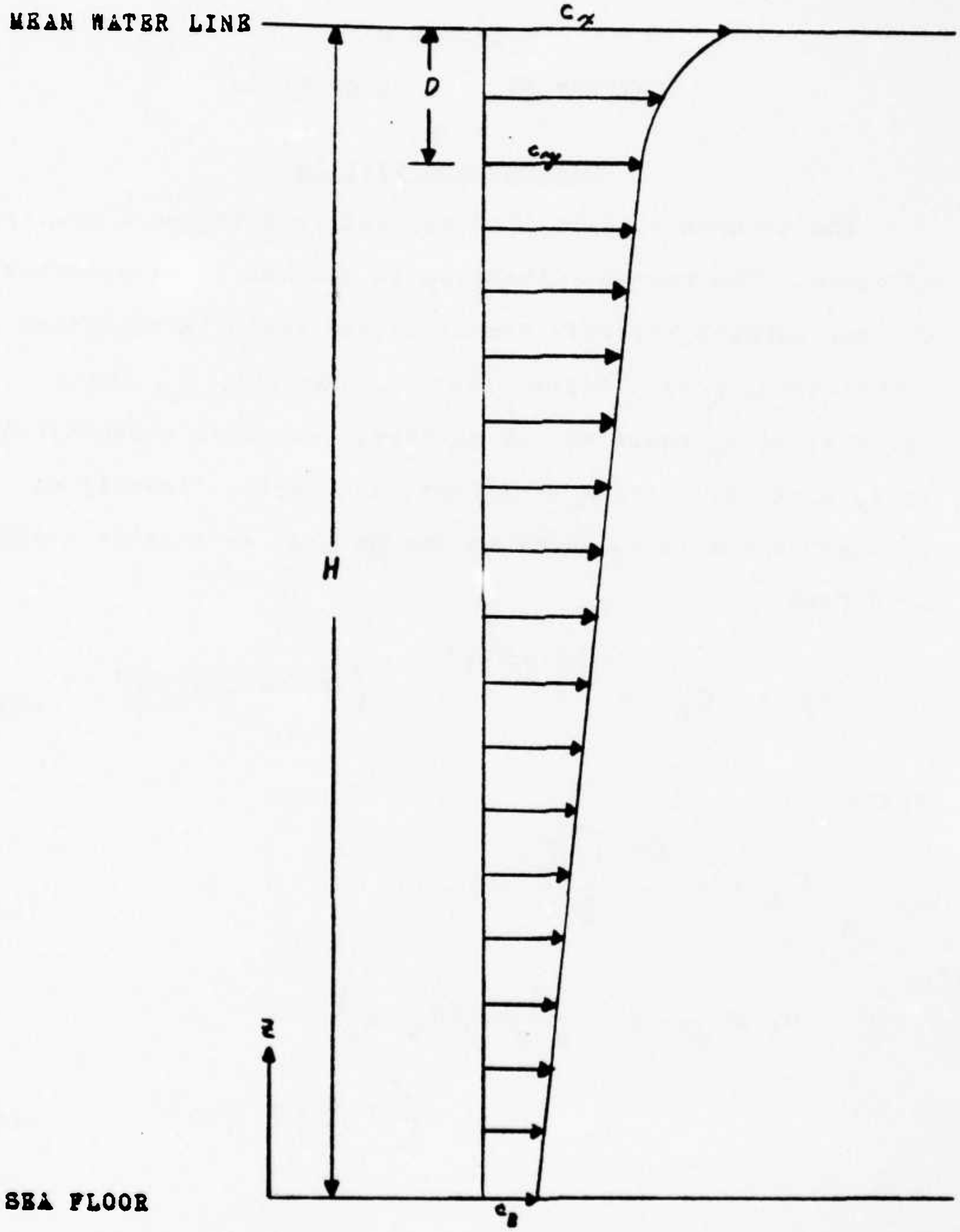


Figure C-1. Current Profile

C.2 Drag Coefficients

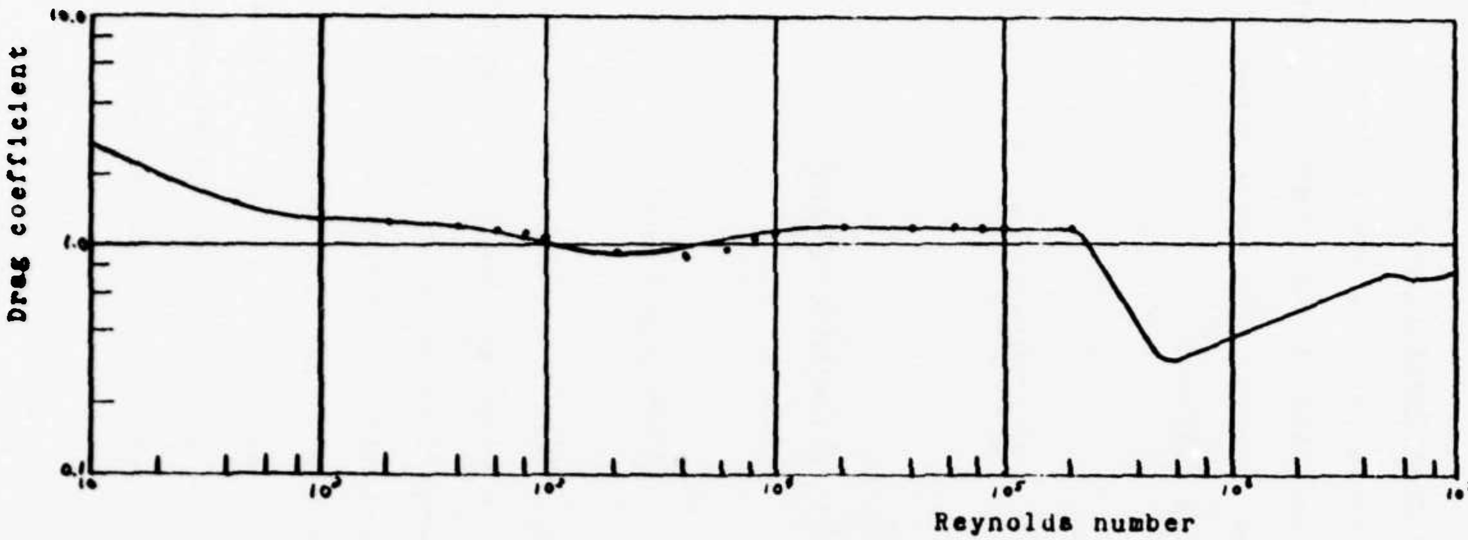
The drag coefficients for both the cable and the spherical buoys are specified in the program for different ranges of Reynolds numbers. The cable normal drag coefficient is given as follows:

$$C_{DN} = 1.2\, e^{-\left[\frac{Re - (6 \times 10^{2})}{(8.0 \times 10^{2})}\right]} \qquad (2.0 \times 10^{2}) \le Re < (2.5 \times 10^{3}) \tag{C3a}$$

$$C_{DN} = 0.9\, e^{\left[\frac{Re - (2.5 \times 10^{3})}{(4.3 \times 10^{4})}\right]} \qquad (2.5 \times 10^{3}) \le Re < (1.5 \times 10^{4}) \tag{C3b}$$

$$C_{DN} = 1.2 \qquad (1.5 \times 10^{4}) \le Re < (2.0 \times 10^{5}) \tag{C3c}$$

The lower bound for the Reynolds number for the cable normal drag coefficient is given as (2.0×10^2), which, for a 20,000 foot long 2 inch diameter cable (which is used in the present study), corresponds to a normal drag of 1.5 pounds. The upper bound is (2.0×10^5). (The maximum Reynolds number expected in this study is (3.6×10^4).) Figure C-2 shows a comparison between the approximations of equations (C3) and the actual normal drag coefficient for smooth cylinders.[39]



— Actual values
··· Approximate values

Figure C-2. Actual Normal Drag Coefficients for Circular Cylinders

The cable tangential drag coefficient is specified as:

$$C_{DT} = 0.006\,e^{-\left[\frac{Re-(2\times10^3)}{(2.2\times10^5)}\right]} \qquad (2.0\times10^3) \le Re \le (2.0\times10^5) \qquad \text{(C4)}$$

The lower bound for Re is (2.0×10^3) which gives a tangential drag of 2.3 pounds for the cable used in this study; the upper bound is (2.0×10^5). (Re is not expected to exceed (3.5×10^4) in this study.) Figure C-3 compares the values calculated from equation (C4) and the actual tangential drag coefficients for smooth cylinders.[28]

The drag coefficient for a spherical buoy is given as follows:

$$C_{DS} = 0.5 \qquad (3.0\times10^4) \le Re \le (2.0\times10^5) \qquad \text{(C5a)}$$

$$C_{DS} = 0.5\,e^{-\left[\frac{Re-(2\times10^5)}{(4.9\times10^4)}\right]} \qquad (2.0\times10^5) \le Re < (2.5\times10^5) \qquad \text{(C5b)}$$

$$C_{DS} = 0.18\,e^{\left[\frac{Re-(2.5\times10^5)}{(1.4\times10^6)}\right]} \qquad (2.5\times10^5) \le Re < (4.0\times10^5) \qquad \text{(C5c)}$$

$$C_{DS} = 0.2 \qquad (4.0\times10^5) \le Re \le (1.0\times10^7) \qquad \text{(C5d)}$$

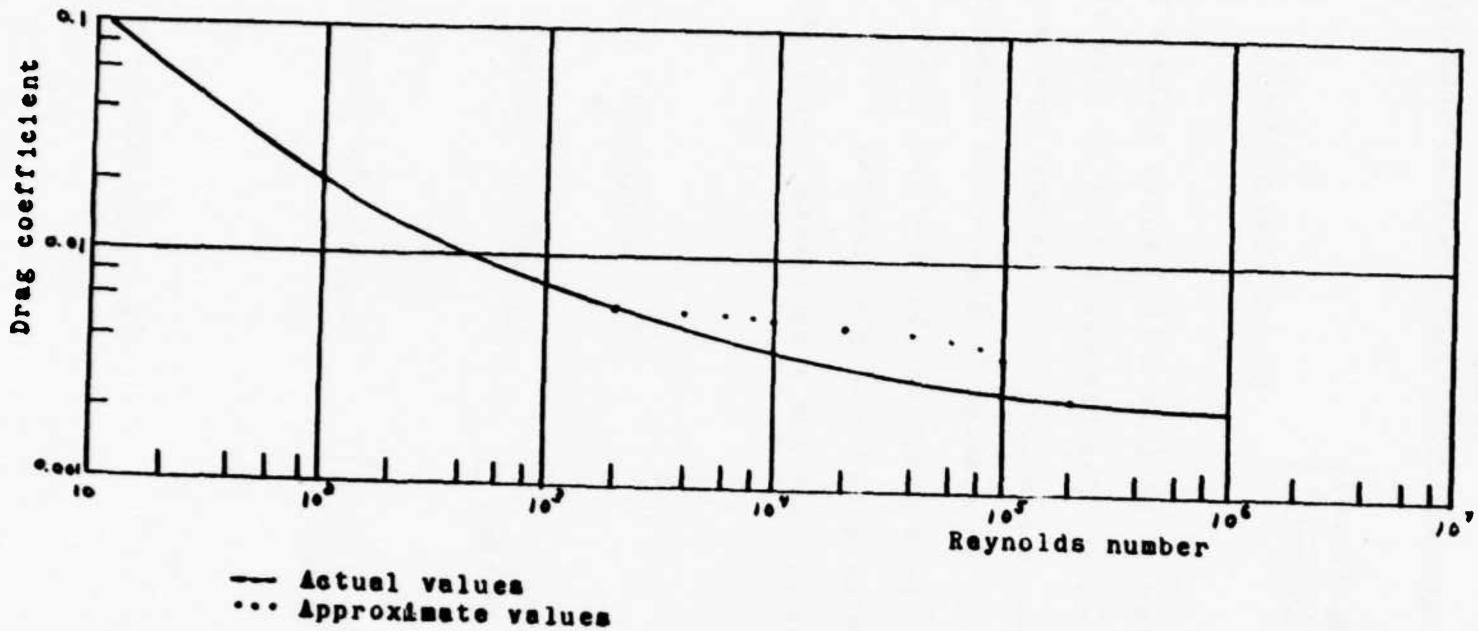


Figure C-3. Actual Tangential Drag Coefficients for Circular Cylinders

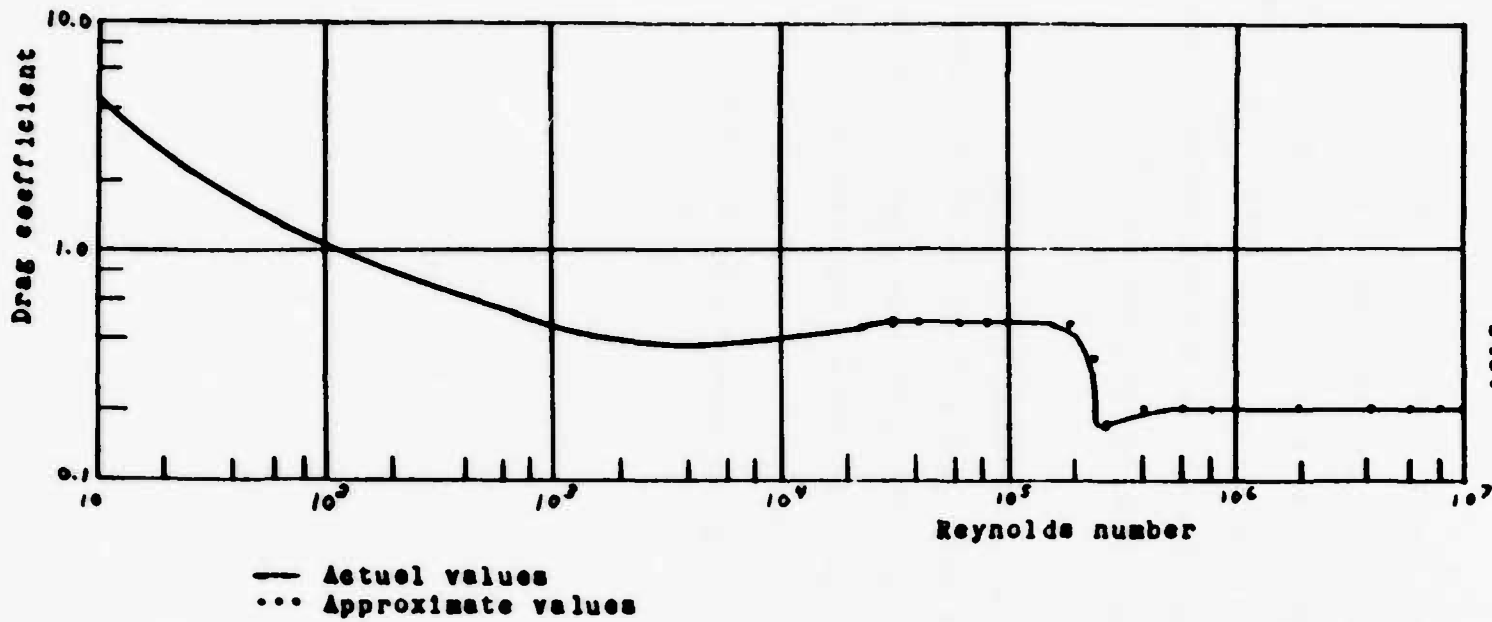


Figure C-4. Actual Drag Coefficients for Spheres

The lower bound for Re is (3.0×10^4), which, for a 6 foot diameter spherical buoy, corresponds to a drag of 0.09 pounds. The upper bound is (1.0×10^7). (The maximum value for Re in this study is (1.3×10^6).) Figure C-4 gives a comparison between the approximations of equations (C5) and the actual drag coefficient for a sphere.[28,39]

C.3 Possible Buoy Systems

There are several buoy systems which the program is capable of handling. The present program allows for a maximum of only two subsurface buoys but, with minimal alterations to the program, more buoys could be added. Figures C-5, C-6, and C-7 show the three possible system configurations.

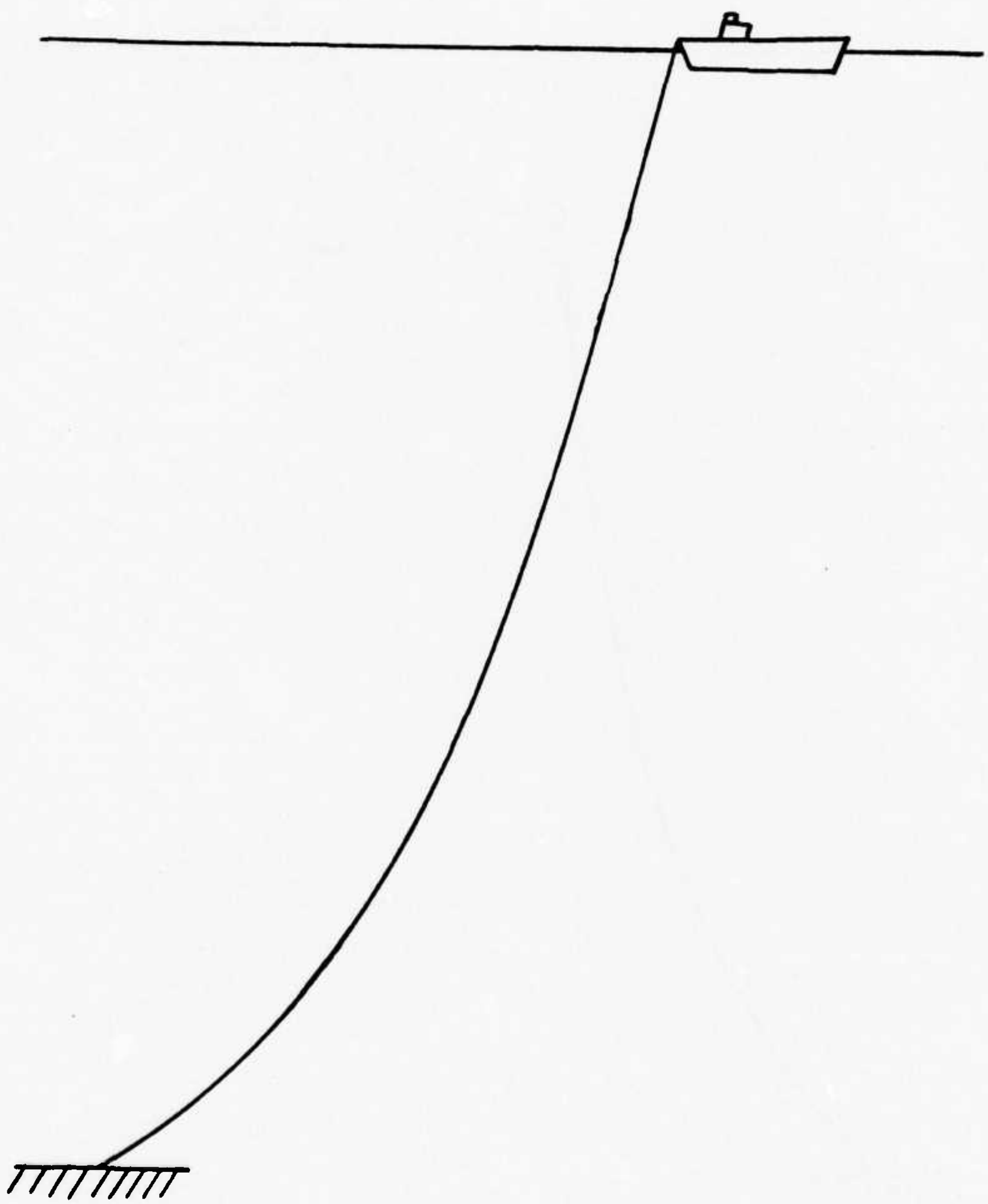


Figure C-5. System With No Buoys

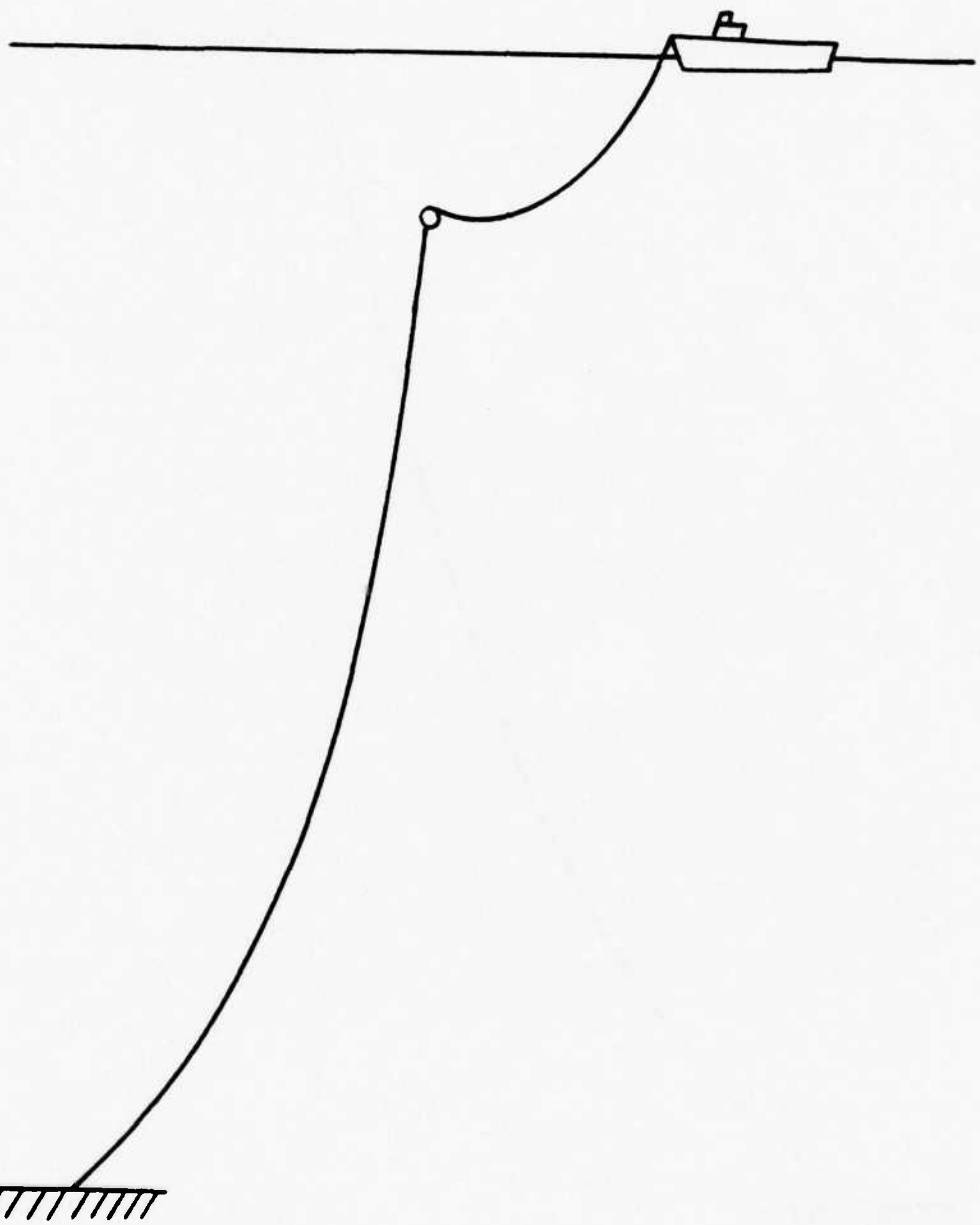


Figure C-6. System With One Buoy

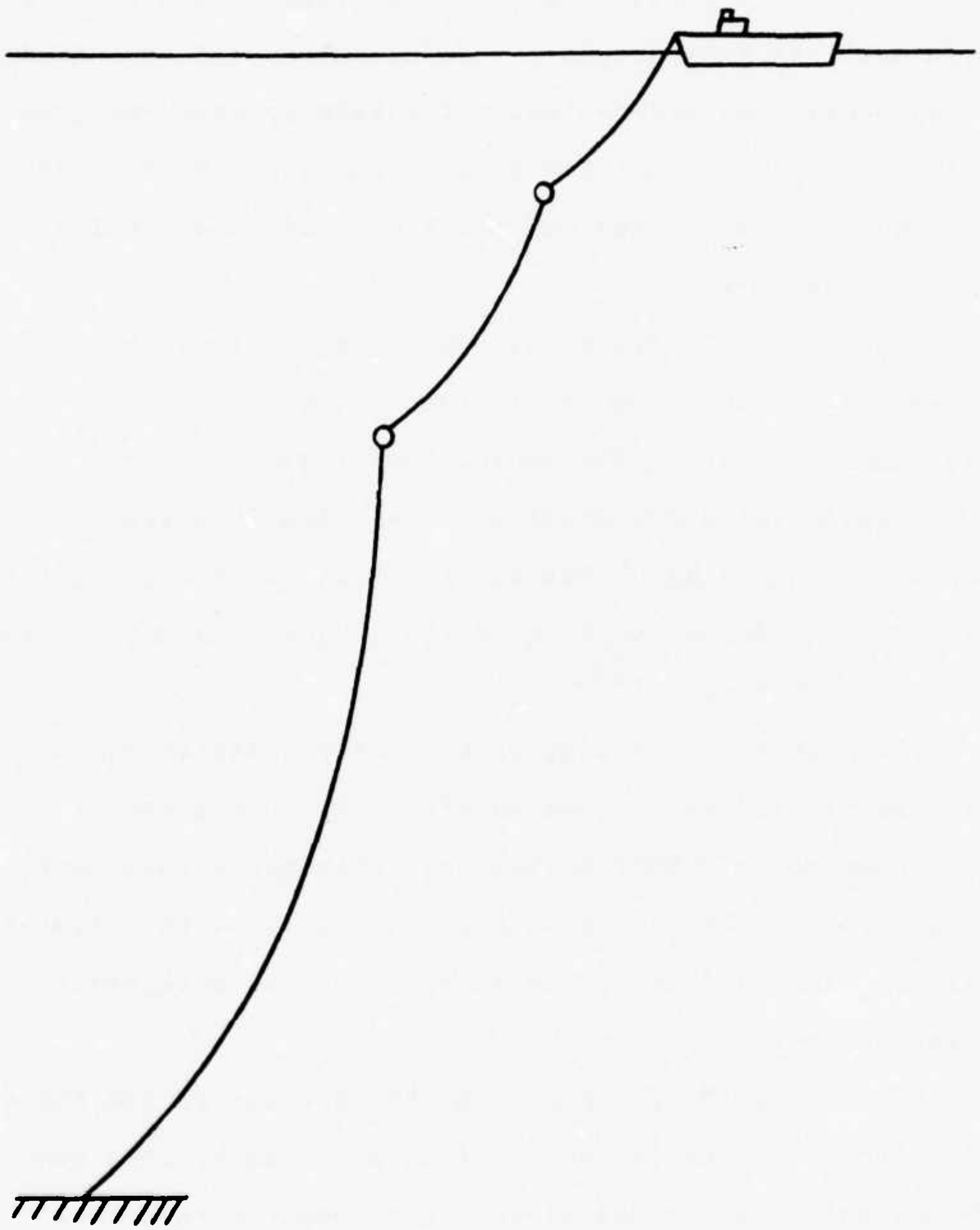


Figure C-7. System With Two Buoys

C.4 Flow Charts

The steady state model is subdivided into a main program and five subroutines. (The dynamic model is included in an additional subroutine.) The main program performs very few calculations; its purpose is to guide the program through the subroutines and print and plot the results. (See figure C-8.)

Subroutine CONFIG specifies the cable equations; it gives the tension, the two angles, and the position at regular intervals along the cable. (See figure C-9.)

Subroutine RUNGE gives a Runge-Kutta numerical solution for the integration of the differential equations. (It is called from CONFIG and from DYMICS.) This subroutine was developed by White.[25]

Subroutine ANGLE simply gets any two angles to be between $-\pi$ and π radians or -180 and 180 degrees.

Subroutine SUBSRF solves the force and moment equilibrium equations of the subsurface buoy to give the tension, angles, and position of the second point of attachment. (See figure C-10.)

Subroutine TENCOR corrects the tensions at the anchor in order to reduce the error between the calculated location of the ship and the actual location.(See figure C-11.)

Subroutine DYMICS gives the positions, velocities,

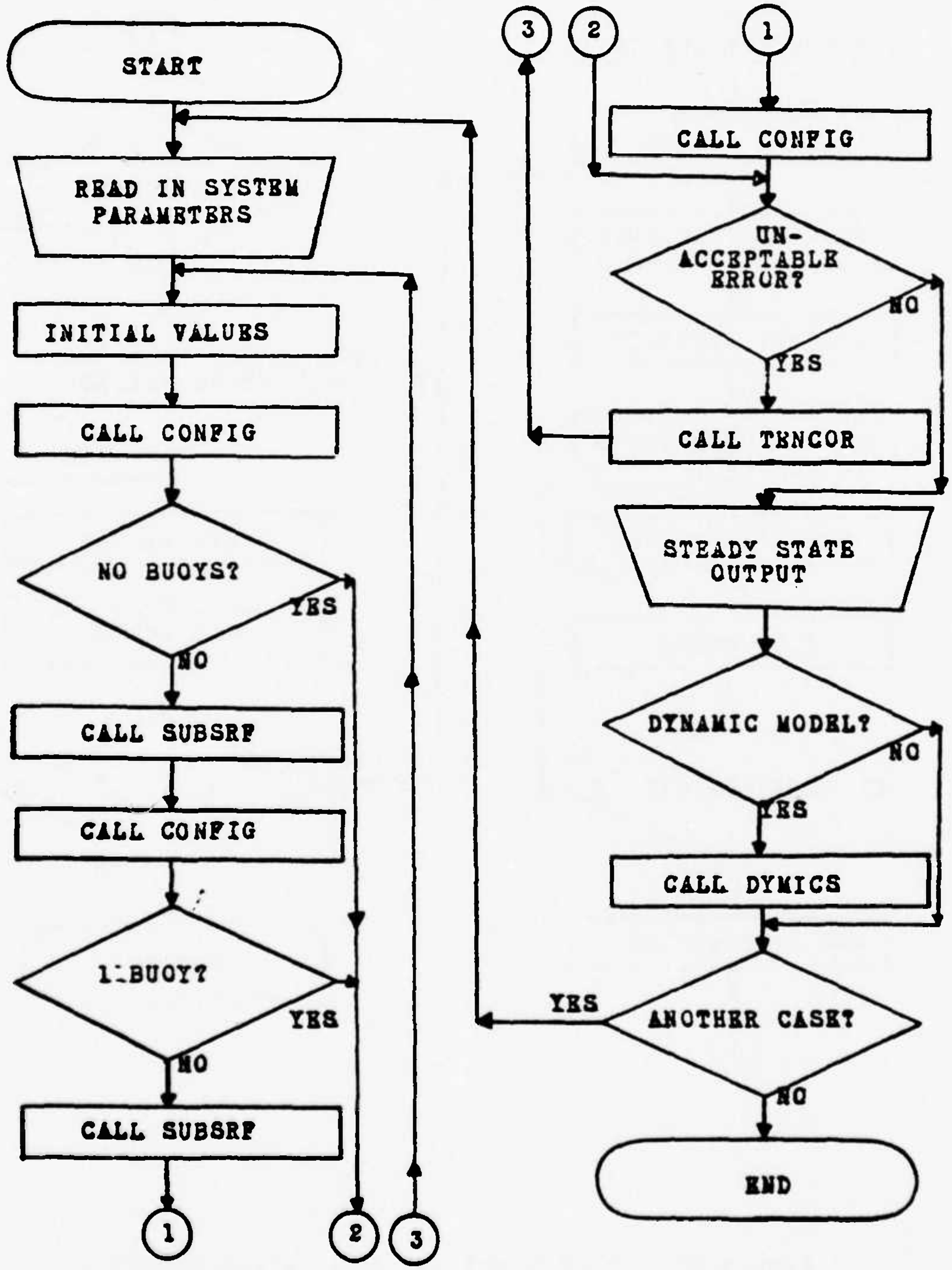


Figure C-8. Flow Chart for Main Program

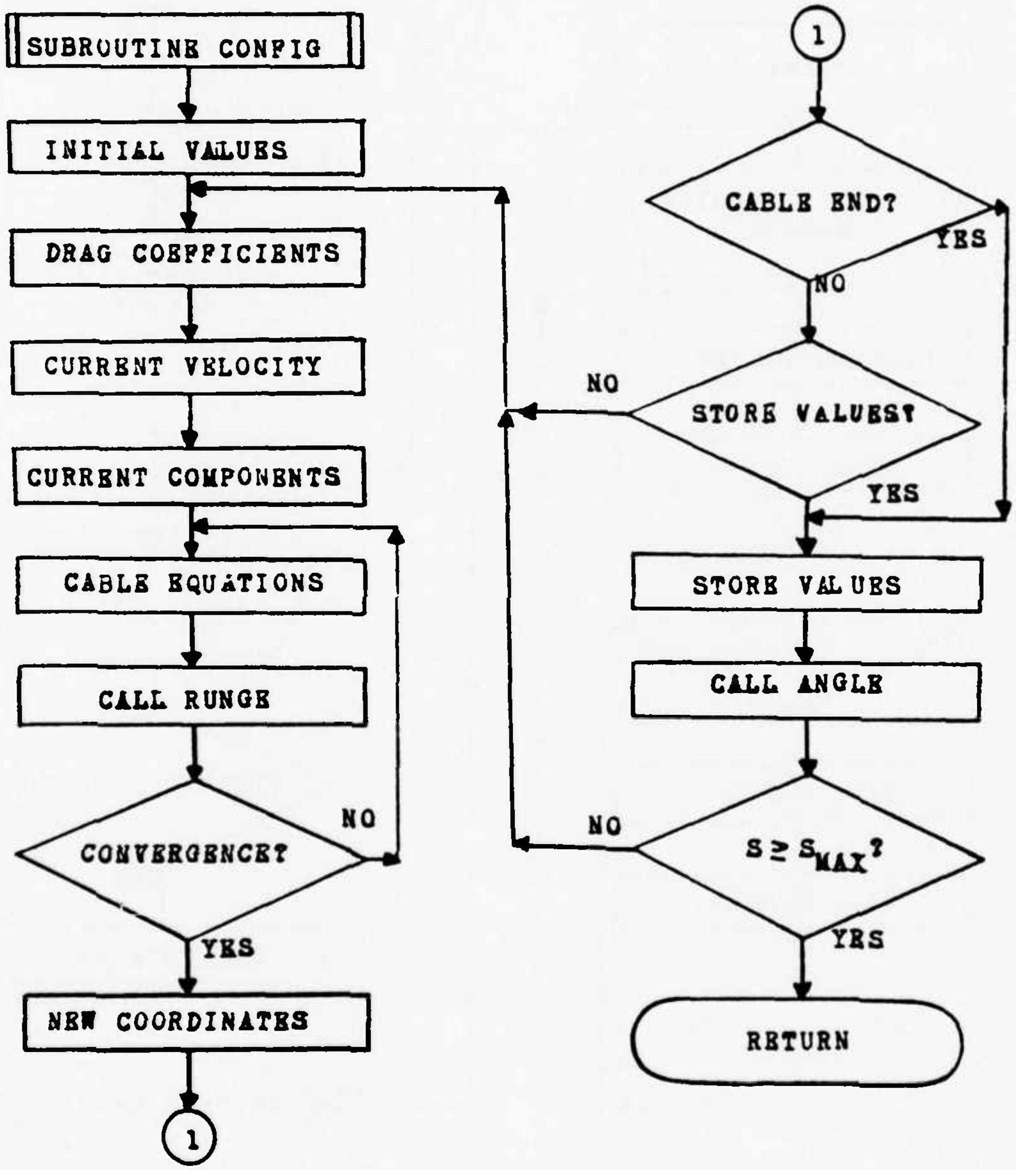


Figure C-9. Flow Chart for Subroutine CONFIG

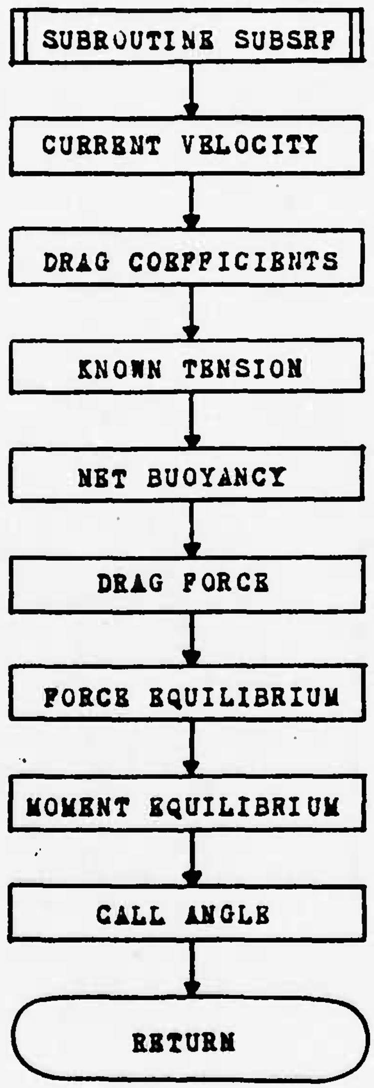


Figure C-10. Flow Chart for Subroutine SUBSRF

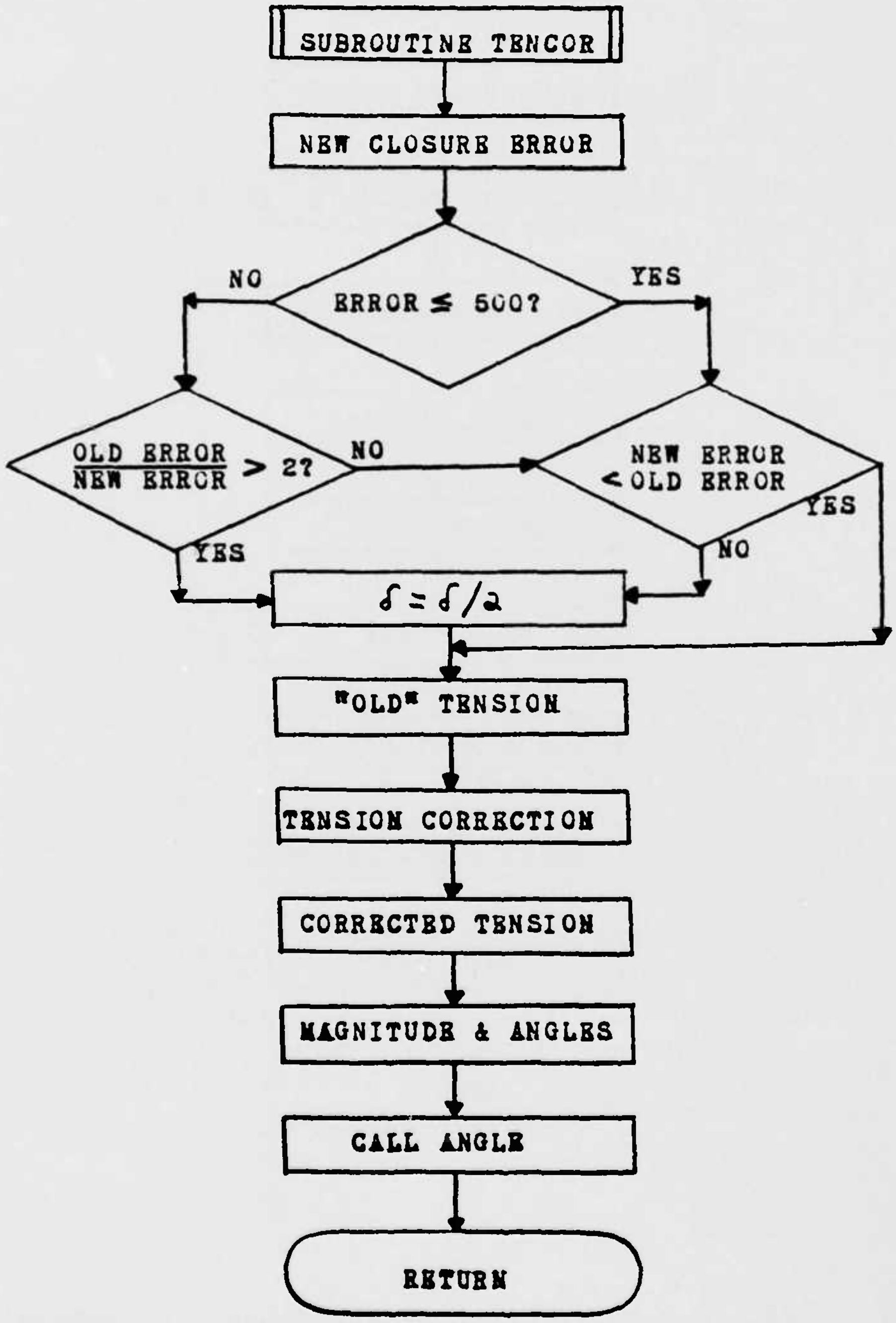


Figure C-11. Flow Chart for Subroutine TENCOR

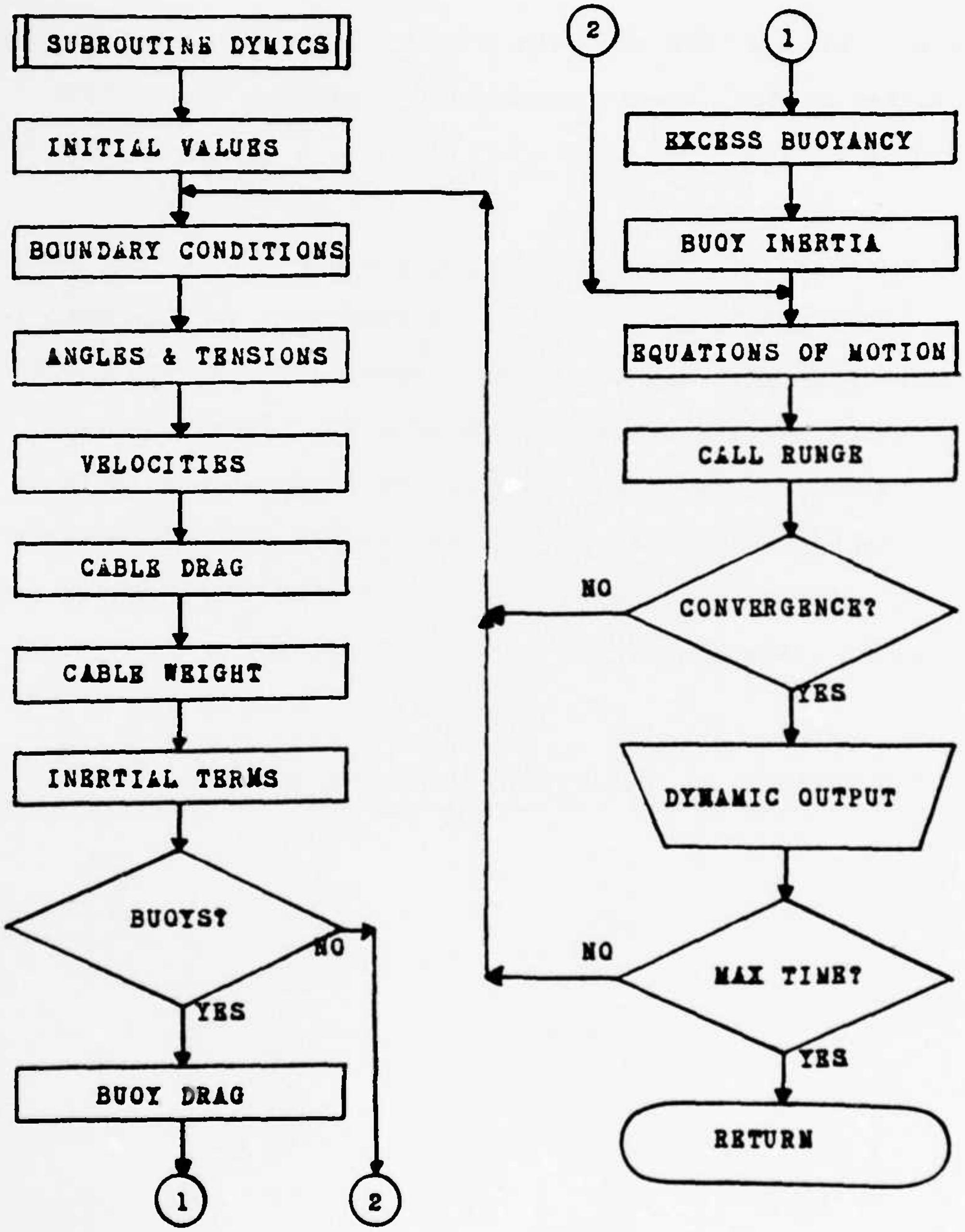


Figure C-12. Flow Chart for Subroutine DYMICS

accelerations, and tensions of the system when it is being excited by the dynamic motions of a surface ship. (See figure C-12.)

C.5 Input Data Cards

The program was designed to allow the user as much freedom as possible in choosing various parameters for the system. Thus, maximum use was made of inputting data. The order and format of each parameter of each card required for the steady state model is given below in table C-1. (Do not include cards 3 to 203 if IDYMIC = 0; do not include cards 104 to 203 if BETA = 0 or 180.)

CARD NUMBER	PARAMETER	COLUMNS	FORMAT
1	NCB	1-10	I10
	NCD	11-20	I10
	NCE	21-30	I10
	IDYMIC	31-40	I10
	IPLOT	41-50	I10
2	EPSLNA	1-10	F10.2
	NOITER	11-20	I10
3	BETA	1-10	F10.5
	TMMAX	11-20	F10.5
4-103	AMPZ	1-10	F10.4
	OMEGAZ	11-20	F10.4
	PHANGZ	21-30	F10.4

Table C-1. Order of Input Data Cards

CARD NUMBER	PARAMETER	COLUMNS	FORMAT
104-203	AMPX	1-10	F10.4
	OMEGAX	11-20	F10.4
	PHANGX	21-30	F10.4
204	XCHAR	1-6	A6
	YCHAR	7-12	A6
	ZCHAR	13-18	A6
	XCHRR	19-24	A6
	YCHRR	25-30	A6
	ZCHRR	31-36	A6
	VELX	37-42	A6
	VELY	43-48	A6
	VELZ	49-54	A6
	TEN	55-60	A6
	TIM	61-66	A6
205	CX	1-10	F10.9
	D	11-20	F10.9
	CY	21-30	F10.9
	CB	31-40	F10.9
	THEC	41-50	F10.9
206	IBUOY	1-10	I10
	RA	11-20	F10.2
	PA	21-30	F10.2
	RB	31-40	F10.2
	PB	41-50	F10.2
207	SAD	1-10	F10.3
	EAD	11-20	F10.3
	WAD	21-30	F10.3
	DAD	31-40	F10.3
	DSAD	41-50	F10.3
208	SEG	1-10	F10.3
	EEG	11-20	F10.3
	WEG	21-30	F10.3
	DEG	31-40	F10.3
	DSEG	41-50	F10.3

Table C-1. Order of Input Data Cards (Cont'd)

CARD NUMBER	PARAMETER	COLUMNS	FORMAT
209	SGT	1-10	F10.3
	EGT	11-20	F10.3
	WGT	21-30	F10.3
	DGT	31-40	F10.3
	DSGT	41-50	F10.3
210	TITLE	1-6	A6
211	G	1-10	F10.2
	H	11-20	F10.2
	ICASE	21-30	I10

Table C-1. Order of Input Data Cards (Cont'd)

The parameters used in table C-1 may be described as follows:

NCB = number of times cards 210 and 211 will be repeated for one set of values of cards 1 thru 209.

NCD = number of times cards 206 thru 211 will be repeated for one set of values of cards 1 thru 205.

NCE = number of times card 206 will be repeated for one set of values of cards 1 thru 204.

IDYMIC = 0 if only the steady state model is desired.
= 1 if both the steady state and dynamic models are desired.

IPLOT = 0 if no plots are desired.
= 1 if plots are desired.

EPSLNA = maximum closure error at ship (feet) for steady state model.

NOITER = maximum number of iterations per case for steady state model.

BETA = ship heading in degrees (following seas = 0°, beam seas = 90°, head seas = 180°).

TMMAX = length of time in seconds for which the dynamic simulation is desired.

AMPZ = amplitude in feet of heave of ship at frequency OMEGAZ (in radians) and phase angle PHANGZ (in radians).

AMPX = amplitude in feet of sway of ship at frequency OMEGAX (in radians) and phase angle PHANGX (in radians).

XCHAR,
YCHAR,
ZCHAR = labels on x-axis, y-axis, and z-axis respectively on plots of steady state model.

XCHRR,
YCHRR,
ZCHRR = labels on x-axis, y-axis, and z-axis respectively on plots of dynamic model.

VELX,
VELY,
VELZ = labels for velocity components in x, y, and z directions respectively on plots of dynamic model.

TEN = label for tension on plots of dynamic model.

TIM = label for time on plots of dynamic model.

CX = current speed in knots at the surface.

D = depth in feet above which the current variation is exponential and below which the current variation is linear.

CY = current speed in knots at depth D

CB = current speed in knots at ocean bottom.

THBC = current direction in degrees, measured positive counterclockwise from the y-axis.

IBUOY = total number of buoys (0, 1, or 2).

BA = excess buoyancy in pounds of first buoy (displacement minus buoy air weight).

PA = density of first buoy in pounds per cubic foot.

BB = excess buoyancy in pounds of second buoy.

PB = density of second buoy in pounds per cubic foot.

SAD = unstretched length of cable in feet between the anchor and the first buoy (between the anchor and ship if no buoys); this length of cable is referred to as the first segment.

EAD = modulus of elasticity in pounds per square inch of the first segment.

WAD = weight in water of first segment in pounds per foot.

DAD = outside diameter in inches of first segment.

DSAD = strength member diameter in inches of first segment (See figure 1.).

SEG = unstretched length of cable in feet between the first buoy and the second buoy (between the first buoy and ship if only one buoy); this length of cable is referred to as the second segment
= if no buoys

EEG,
WEG,
DEG,
DSEG = are analogous to EAD, WAD, DAD, and DSAD respectively, except that they refer to the second segment
= if no buoys

SGT = unstretched length of cable in feet between the second buoy and the ship; this length of cable is referred to as the third segment.
= 0 if no buoys or only one buoy.

EGT,
WGT,
DGT,
DSGT = are analogous to EAD, WAD, DAD, and DSAD respectively except that they refer to the third segment.
= 0 if no buoys or only one buoy.

TITLE = title printed on all plots.

G = projected length in feet in the horizontal plane between the anchor and the ship.

H = water depth in feet.

ICASE = case number.

The order of the cards resembles a large DO loop for the program:

```
              (DATA CARDS 1 THRU 204)
      DO 1 NCBC = 1, NCB
              (DATA CARD 205)
      DO 2 NCDC = 1, NCD
              (DATA CARDS 206 THRU 209)
      DO 3 NCBC = 1, NCB
              (DATA CARDS 210 THRU 211)
    3 CONTINUE
    2 CONTINUE
    1 CONTINUE
```

Thus, there is only one of cards 1 thru 204, there are NCB of card 205, there are NCB X NCD of cards 206 thru 209, and there are NCB X NCD X NCB of cards 210 and 211.

This means that the ship's position and water depth are varied first, then the parameters of the cables and buoys, and finally the current velocity.

C.6 Program Convergence and Limitations

The steady state program has been applied to a number of cases; however, they have not been exhaustive. Convergence for the iteration process which finds the tension at the anchor has been found to take place after about 18 to 26 iterations.

Problems have been encountered with certain configurations. Very high tension cases, where the cable must elongate a good deal, are slow to converge. For example, in one such case, the maximum tensions in the cable reached 30,000 pounds after 70 iterations. (Higher tensions were expected.) For the purposes of this study, though, tensions of this magnitude will not exist. (The maximum allowable steady state tension is 8000 pounds due to material limitations.)

Slack cases have also had problems with convergence. A slack mooring, as used here, is defined to be a configuration in which a portion of the lower section of cable remains on the bottom (that is, it lies in the horizontal

plane). For this study, such cases are not of interest for two reasons. First, such tensions will always be in the acceptable range. Second, a slack cable is undesirable because of possible problems with the cable tangling itself.

It should be noted that the program does not account for certain physical constraints on the cable attachment at a subsurface buoy. Certain cases may produce a configuration where the cable "goes inside" the buoy. The program cannot apply this geometrical limitation to the cable angles at the buoy.

This program was run on a UNIVAC 1108 digital computer at the Naval Underwater Systems Center. The approximate CPU time in the steady state was two minutes per case, where the closure error (EPSLNA) was taken to be 10 feet. Approximate CPU time for the dynamic model in minutes was given by

$$\text{CPU time} = 0.004 \left(\frac{\text{TMMAX}}{b}\right)$$

where TMMAX is time in seconds the system is allowed to run and b is the step size in time (seconds).

Appendix D

SHIP DESCRIPTION

The ship used in this study is one of the Agor class. Its parameters are given in tables D-1 and D-2, where the terms are defined to be:

CB	:	block coefficient, defined as volume of the displaced fluid divided by (midship beam • midship draft • ship length between perpendiculars) (nondimensional)
XLBP	:	ship length between perpendiculars (feet)
BEAM	:	midship beam (feet)
DRAFT	:	midship draft (feet)
XCG	:	longitudinal center of gravity measured from the waterline (positive up) (feet)
VCG	:	vertical center of gravity measured from the waterline (positive up) (feet)
GM	:	metacentric height (feet)
RYY	:	radius of gyration about the y-axis (feet)
RXX	:	radius of gyration about the x-axis (feet)
RZZ	:	radius of gyration about the z-axis (feet)
XZI	:	mass moment of inertia about the x-z axis (slug • feet squared)
WSURFA	:	wetted surface (feet squared)
ST	:	station number (F.P.= 0, A.P.= 10) (nondimensional)
XI	:	distance to ship station ST measured from amidship positive forward (feet)

YM : full beam at waterline of station ST (feet)

ZM : draft at station ST (feet)

SIGMA : area coefficient of station ST (defined as section area divided by beam · draft of station ST) (nondimensional)

ZCB : vertical center of buoyancy of station ST measured from the waterline positive up (feet)

GIRTH : girth of ship station ST (feet)

ALPH : angle between ship side and vertical, required only for IWBK = 1 (degrees)

IWBK = 1 : sections with a deep U or V shape and small radius at the keel (typically at the forward portion of the ship)

IWBK = 3 : sections having a triangular shape as the extreme aft section of a cruiser stern ship

IWBK = 4 : sections which are unlikely to produce eddies as the ship rolls

Figure D-1 indicates the coordinate system used at the ship. (This is for the seakeeping program only.)

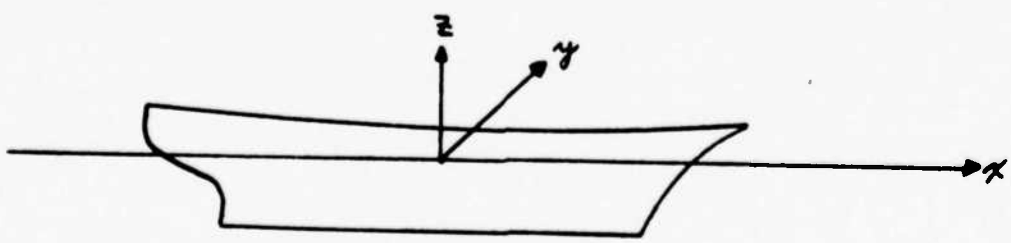


Figure D-1. Coordinate System of Ship

The (x, y, z) coordinates of the point for which motion computations were performed are (98.0, 0, 0). The x coordinate of the origin for motion computations was assumed to be the same as the XCG of the ship. Regular wave frequencies (wave length / ship length) used in this study are given as: 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0, 1.1, 1.2, 1.3, 1.4, 1.5, 1.6, 1.7, 1.8, 1.9, 2.0, 2.25, 2.5, 2.75, and 3.0.

CB	=	0.43
XLBP	=	196.0
BEAM	=	39.0
DRAFT	=	14.25
XCG	=	-2.0
VCG	=	3.1
GM	=	1.95
RYY	=	49.0
RXX	=	15.6
RZZ	=	49.0
XZI	=	0.0
WSURFA	=	8073.0

Table D-1. Ship Parameters

ST	XI	YM	ZM	SIGMA	ZCB	GIRTH	ALPH	IWBK
0	98.0	0.0	0.0	0.000	0.0	26.8		4
½	88.2	4.2	13.2	0.538	-4.3	29.8	10.0	1
1	78.4	9.0	13.8	0.598	-4.4	38.7	17.0	1
2	58.8	18.8	13.9	0.678	-4.4	56.6	21.0	1
3	39.2	28.6	14.1	0.736	-4.8	71.5		4
4	19.6	36.0	14.2	0.758	-5.0	84.9		4
5	0.0	39.0	14.2	0.782	-5.1	90.8		4
6	-19.6	39.0	14.2	0.736	-4.9	92.3		4
7	-39.2	36.8	14.1	0.644	-4.6	77.4		4
8	-58.8	31.6	14.0	0.504	-3.9	61.0		3
9	-78.4	20.2	13.9	0.336	-3.0	56.6		3
9½	-88.2	11.6	3.0	0.488	-1.2	23.8		3
10	-98.0	0.0	0.0	0.000	0.0	0.0		4

Table D-2. Ship Station Parameters

Appendix B

COMPUTER PROGRAM LISTING

This appendix contains the program used to simulate the cable-buoy-ship systems described in this study.

@FOR,SI STEADY,STEADY
FOR OE2B-01/11/77-04:56:42 (,0)

MAIN PROGRAM

STORAGE USED: CODE(1) 003227; DATA(0) 004370; BLANK COMMON(2) 000000

EXTERNAL REFERENCES (BLOCK, NAME)

0003	CONF16
0004	SUBSHF
0005	TEMCOM
0006	MOVES6
0007	SETSMG
0010	BEGIN3
0011	OBJCT6
0012	SUBJ3D
0013	GRPH3D
0014	PNT3D
0015	SHDE3D
0016	PAGE6
0017	SUBJE6
0020	GRAPH6
0021	POINT6
0022	LINES6
0023	EXIT6
0024	DYNICS
0025	NINTRS
0026	NRULS
0027	NI02$
0030	ALOG
0031	CBRT
0032	NPRTS
0033	SQRT
0034	NSTOP$

STORAGE ASSIGNMENT (BLOCK, TYPE, RELATIVE LOCATION, NAME)

0000	003706	10F	0001	003106	1030L	0001	001770	1041G	0001	003135	1050L	0001	002027	1076G
0000	003736	109F	0000	003701	11F	0000	003742	110F	0001	003207	1100L	0001	001407	111L
0000	003754	112F	0001	002064	1126G	0001	001413	113L	0000	003700	12F	0000	003765	120F
0001	002320	1226G	0001	002356	1245G	0001	002415	1264G	0001	000033	135G	0001	003022	1360G
0001	003047	1375G	0001	003075	1412G	0001	003110	1424G	0001	000057	151G	0000	004014	160F
0001	001436	161L	0000	004027	162F	0001	001442	163L	0001	000072	166G	0000	004041	170F
0000	004053	176F	0000	004054	180F	0001	001473	195L	0000	003721	20F	0000	003715	21F
0000	004066	210F	0000	004076	212F	0001	000154	22L	0000	004121	220F	0000	004104	226F
0001	000155	23L	0001	001637	230L	0000	003714	24F	0000	004142	240F	0001	001633	243L
0001	001633	244L	0000	003723	25F	0000	004152	250F	0000	003710	26F	0000	004166	260F
0001	001650	261L	0001	001664	262L	0001	001677	263L	0000	004176	270F	0001	000116	28L
0000	004205	280F	0001	000451	30L	0001	000076	32L	0000	003712	33F	0001	000070	35L
0000	004217	350F	0000	004236	360F	0000	004267	361F	0001	001777	362L	0001	000076	37L
0001	000156	38L	0000	004273	380F	0001	000252	39L	0000	004300	390F	0000	003717	40F
0000	004304	410F	0000	004313	419F	0001	002110	421L	0000	004310	430F	0000	003725	46F
0001	000627	48L	0001	000730	49L	0001	001112	491L	0001	001133	492L	0001	001153	493L
0001	002271	510L	0001	001362	550L	0001	001010	58L	0001	001105	59L	0001	002543	600L

```
0001   002645 610L    0001   002747 620L    0001   002447 660L    0000   003702 8F      0000   003704 9F
0001   002760 995L    0000 R 002271 AMPX    0000 R 002436 AMPZ    0000 R 003436 BETA    0000 R 003460 CR
0000 R 003455 CA      0000 R 003457 CT      0000 R 003462 C2      0000 R 003456 D       0000 R 003476 DAD
0000 R 003503 DEG     0000 R 003656 DELTH   0000 R 003541 DELIO   0000 R 003510 DGT     0000 R 002225 DL
0000 R 003661 DMA     0000 R 003663 DMB     0000 R 002233 DOUI    0000 R 002211 DS      0000 R 003477 DSAD
0000 R 003504 DSEG    0000 R 003511 DSGT    0000 R 003465 EA      0000 R 003474 EAD     0000 R 003467 ER
0000 R 002217 ECB     0000 R 003501 EEG     0000 R 003506 EGT     0000 R 003434 EPSLMA  0000 R 003647 ERS
0000 R 003657 ESR     0000 R 003537 ETA     0000 R 003547 ETAD    0000 R 003655 ETAH    0000 R 002255 EXB
0000 R 003514 G       0000 R 003664 GG      0000 R 003515 H       0000 R 003526 HOOLD   0000 R 003645 HHIA
0000 R 003650 HH1B    0000 R 003646 HH2A    0000 R 003651 HH2B    0000 I 003554 IATCH1  0000 I 003555 IATCH2
0000 I 003464 IDDOT   0000 I 003516 ICASE   0000 I 003546 IDELTA  0000 I 003432 ICYMIC  0000 I 003433 IPLOT
0000 I 003600 IHHOR   0000 I 003531 ISRCT   0000 I 003553 ISRFB   0000 I 003551 ISRF1   0000 I 003552 ISRF2
0000 I 003545 ITEMIS  0000 I 003550 IIRTSS  0000 I 003565 LMENT   0000 I 003577 LS      0000 I 003621 LT
0000 I 003540 LTEPA   0000 I 003532 LTME    0000 I 003533 LTM1    0000 I 003534 LTM2    0000 I 003643 LU
0000 I 003440 N       0000 I 003674 NB      0000 I 003676 NB3     0000 I 003427 NCB     0000 I 003512 NCBC
0000 I 003430 NCD     0000 I 003463 NCDC    0000 I 003431 NCE     0000 I 003454 NCEC    0000 I 003675 NF
0000 I 003677 NE3     0000 I 003435 NOITER  0000 I 003566 NSG1    0000 I 003610 NSG2    0000 I 003632 NSG3
0000 I 003556 NUP     0000 R 002603 OMEGAX  0000 R 002750 OMEGAZ  0000 R 001604 P       0000 R 003466 PA
0000 R 003470 PB      0000 R 003665 PERELG  0000 R 003115 PHANGX  0000 R 003262 PHANGZ  0000 R 003576 PHIF
0000 R 003604 PHIG    0000 R 003620 PHIH    0000 R 003525 PHII    0000 R 003626 PHIII   0000 R 003642 PHIJ
0000 R 003544 PHIPA   0000 R 000226 PHIS    0000 R 000606 PHIT    0000 R 001166 PHIU    0000 R 003654 PHIW
0000 R 002114 PLUI    0000 R 003471 RA      0000 R 002247 RAD     0000 R 003472 RB      0000 R 003601 RPC
0000 R 003623 RBE     0000 R 003522 RHOA    0000 R 003521 RHOW    0000 R 003473 SAD     0000 R 003500 SEG
0000 R 003567 SF      0000 R 003565 SGT     0000 R 003611 SH      0000 R 003570 SIF     0000 R 003612 SIH
0000 R 003634 SIJ     0000 R 000322 SIS     0000 R 000702 SIT     0000 R 001262 SIU     0000 R 003633 SJ
0000 R 003564 SL      0000 R 003560 SOI     0000 R 000264 SS      0000 R 000644 ST      0000 R 003557 STRI
0000 R 001224 SU      0000 R 003452 TEN     0000 R 003574 TF      0000 R 003602 TG      0000 R 003616 TH
0000 R 003461 THEC    0000 R 003575 THETAF  0000 R 003603 THETAG  0000 R 003617 THETAH  0000 R 003524 THETAI
0000 R 003641 THETAJ  0000 R 000170 THETAS  0000 R 000550 THETAT  0000 R 001130 THETAU  0000 R 003653 THETAW
0000 R 003625 THETII  0000 R 003543 THETPA  0000 R 001356 THETVS  0000 R 001452 THETVT  0000 R 001546 THETVU
0000 R 003624 TII     0000 R 003453 TIM     0000 R 003513 TITLE   0000 R 003640 TJ      0000 R 003437 TMMAX
0000 R 003523 TNSONI  0000 R 003542 TPA     0000 R 000132 TS      0000 R 000512 TT      0000 R 001072 TU
0000 R 003652 TW      0000 R 001320 VCS     0000 R 001414 VCT     0000 R 001510 VCU     0000 R 003447 VELX
0000 R 003450 VELY    0000 R 003451 VEL2    0000 R 003517 WA      0000 R 003475 WAD     0000 R 003520 WR
0000 R 002241 WCG     0000 R 003502 WEG     0000 R 003507 WGT     0000 R 002263 WT      0000 R 003441 XCHAR
0000 R 003444 XCHHR   0000 R 003571 XF      0000 R 003605 XG      0000 R 003613 XH      0000 R 003561 XI
0000 R 003627 XII     0000 R 002164 XIX     0000 R 003635 XJ      0000 R 003671 XMAX    0000 R 003666 XMIN
0000 R 000000 XS      0000 R 000360 XT      0000 R 000740 XU      0000 R 003442 YCHAR   0000 R 003445 YCHRR
0000 R 003572 YF      0000 R 003606 YG      0000 R 003614 YH      0000 R 003562 YI      0000 R 003630 YII
0000 R 002173 YIY     0000 R 003636 TJ      0000 R 003672 YMAX    0000 R 003667 YMIN    0000 R 003530 YOLD
0000 R 003535 YOLS    0000 R 000036 TS      0000 R 000416 YT      0000 R 000776 YU      0000 R 003443 ZCHAR
0000 R 003446 ZCHHR   0000 R 003573 ZF      0000 R 003607 ZG      0000 R 003615 ZH      0000 R 003563 ZI
0000 R 003631 ZII     0000 R 002202 Z12     0000 R 003637 ZJ      0000 R 003673 ZMAX    0000 R 003670 ZMIN
0000 R 003622 ZOF     0000 R 003644 Z06     0000 R 003527 ZOLD    0000 R 003536 ZOLS    0000 R 000074 ZS
0000 R 003660 ZSLS    0000 R 000454 ZT      0000 R 003662 ZTLT    0000 R 001034 ZU

00100    1*   C                                                                        000000
00100    2*   C       STEADY STATE CONFIGURATIONS OF MOORED UMBILICAL CABLE                000000
00100    3*   C                                                                        000000
00101    4*           DIMENSION XS(30),YS(30),ZS(30),TS(30),THETAS(30),PHIS(30),SS(30),S  000000
00101    5*          1IS(30),XT(30),TT(30),ZT(30),TT(30),THETAT(30),PHIT(30),ST(30),SIT(   000000
00101    6*          230),XU(30),YU(30),ZU(30),TU(30),THETAU(30),PHIU(30),SU(30),SIU(30)   000000
00101    7*          3,VCS(30),THETVS(30),VCT(30),THETVT(30),VCU(30),THETVU(30),P(200),P   000000
00101    8*          4LOT(40)                                                              000000
```

```
00103          DIMENSION X1X(7),,1Y(7),Z1Z(7),DS(6),ECB(6),HL(6),DOUT(6),,CH(6),      000001
00103         1RAD(6),EXB(6),WT(6)                                                     000001
00104          DIMENSION AMPX(101),AMPZ(101),OMEGAX(101),OMEGAZ(101),PHANGX(101),      000001
00104         1PHANGZ(101)                                                             000001
00104    C                                                                             000001
00104    C                                                                             000001
00104    C     NCB IS NUMBER OF DIFFERENT DISTANCES(HORIZONTAL DISTANCE BETWEEN        000001
00104    C        ANCHOR AND SHIP) TO BE TESTED FOR ALL BUOY CONFIGURARTIONS           000001
00104    C     NCD IS NUMBER OF DIFFERENT BUOY CONFIGURATIONS TO BE TESTED             000001
00104    C     IPLOT=1 IF 3D PLOT IS WANTED,  =0 IF 3D PLOT IS NOT WANTED              000001
00104    C                                                                             000001
00105          READ 12,NCB,NCD,NCE,IDYMIC,IPLOT                                        000001
00114       12 FORMAT(5I10)                                                            000012
00115       11 FORMAT(4I10)                                                            000012
00115    C                                                                             000012
00115    C     EPSLNA IS MAXIMUM CLOSURE ERROR AT SHIP IN FEET                         000012
00115    C     NOITER IS THE MAXIMUM NUMBER OF ITERATIONS BEFORE TERMINATION           000012
00115    C        FOR EACH CASE                                                        000012
00115    C                                                                             000012
00116          READ 8,EPSLNA,NOITER                                                    000012
00122        8 FORMAT(F10.2,I10)                                                       000020
00123        9 FORMAT(F10.2)                                                           000020
00124       10 FORMAT(2F10.2)                                                          000020
00124    C                                                                             000020
00124    C     BETA IS SHIP HEADING ANGLE (FOLLOWING SEAS=0 DEG,                       000020
00124    C        BEAM SEAS=90 DEG, HEAD SEAS=180 DEG)                                 000020
00124    C     TMMAX IS DESIRED LENGTH OF TIME FOR DYNAMIC CALCULATIONS                000020
00124    C     AMPX AND AMPZ ARE AMPLITUDES                                            000020
00124    C     PHANGX AND PHANGZ ARE PHASE ANGLES                                      000020
00124    C     OMEGAX AND OMEGAZ ARE FREQUENCIES                                       000020
00124    C                                                                             000020
00125          IF(IDYMIC.EQ.0) GO TO 32                                                000020
00127          READ 26,BETA,TMMAX                                                      000022
00133       26 FORMAT(2F10.5)                                                          000033
00134          DO 36 N=1,101                                                           000033
00137          READ 33,AMPZ(N),OMEGAZ(N),PHANGZ(N)                                     000033
00144       36 CONTINUE                                                                000042
00146          IF(BETA.EQ.0..OR.BETA.EQ.180.) GO TO 35                                 000042
00150          DO 34 N=1,101                                                           000057
00153          READ 33,AMPX(N),OMEGAX(N),PHANGX(N)                                     000057
00160       34 CONTINUE                                                                000066
00162       33 FORMAT(3F10.4)                                                          000066
00163          GO TO 37                                                                000066
00164       35 CONTINUE                                                                000072
00165          DO 41 N=1,101                                                           000072
00170          AMPX(N)=0.                                                              000072
00171          OMEGAX(N)=0.                                                            000072
00172          PHANGX(N)=0.                                                            000073
00173       41 CONTINUE                                                                000076
00175       37 CONTINUE                                                                000076
00176       32 CONTINUE                                                                000076
00176    C                                                                             000076
00176    C     3D PLOT AXIS LABELS                                                     000076
00176    C                                                                             000076
00177          READ 24,XCHAR,YCHAR,ZCHAR,XCHRR,YCHRR,ZCHRR,VELX,VELY,,CLZ,TI ,,TIM     000076
00214       24 FORMAT(12A6)                                                            000114
00215          NCEC=0                                                                  000114
```

```
00216      28 CONTINUE                                                          000116
00217         NCEC=NCEC+1                                                       000116
00217   C                                                                       000116
00217   C                                                                       000116
00217   C     CX,D,THEC,AND CZ DESCRIBE THE CURRENT MAGNITUDE AND DIRECTION     000116
00220         READ 21,CX,D,CY,CD,THEC                                           000120
00227      21 FORMAT(5F10.9)                                                    000131
00227   C                                                                       000131
00227   C     CONVERT THEC TO RADIANS                                           000131
00227   C                                                                       000131
00230         THEC=THEC*0.01745                                                 000131
00231         IF(CX.EQ.0.) GO TO 22                                             000134
00233         IF(CY.EQ.0.) GO TO 22                                             000136
00235         IF(D.EQ.0.) GO TO 22                                              000140
00237         CZ=(ALOG(CX/CY))/D                                                000142
00240         GO TO 23                                                          000152
00241      22 CONTINUE                                                          000154
00242         CZ=0.                                                             000154
00243      23 CONTINUE                                                          000155
00244         NCDC=0                                                            000155
00245      38 CONTINUE                                                          000156
00246         NCDC=NCDC+1                                                       000156
00246   C                                                                       000156
00246   C     IBUOY IS TOTAL NUMBER OF BUOYS (0,1,OR 2)                         000156
00246   C     EA IS EXCESS BUOYANCY OF FIRST BUOY (DISPLACEMENT MINUS AIR WT)   000156
00246   C     PA IS FIRST BUOY DENSITY IN LBS PER CUBIC FOOT                    000156
00246   C     RA IS FIRST BUOY RADIUS IN FEET                                   000156
00246   C     EB IS EXCESS BUOYANCY OF SECOND BUOY(DISPLACEMENT MINUS AIR WT)   000156
00246   C     PB IS SECOND BUOY DENSITY IN LBS PER CUBIC FOOT                   000156
00246   C     RB IS SECOND BUOY RADIUS IN FEET ( =0 IF NO BUOYS OR 1 BUOY)      000156
00246   C                                                                       000156
00247         READ 40,IBUOY,EA,PA,EB,PB                                         000160
00256      40 FORMAT(I10,4F10.2)                                                000171
00257         RA=CBRT((EA/(64.4-PA))*(3./(4.*3.14159)))                         000171
00260         RB=CBRT((EB/(64.4-PB))*(3./(4.*3.14159)))                         000203
00260   C                                                                       000203
00260   C     CHARACTERISTICS OF EACH CABLE SEGMENT                             000203
00260   C                                                                       000203
00260   C     S IS CABLE LENGTH IN FEET                                         000203
00260   C     E IS MODULUS OF ELASTICITY IN LBS PER SQUARE INCH                 000203
00260   C     W IS WEIGHT IN WATER IN LBS PER FOOT                              000203
00260   C     D IS OUTSIDE DIAMETER IN INCHES                                   000203
00260   C     DS IS STRENGTH MEMBER DIAMETER IN INCHES                          000203
00260   C                                                                       000203
00260   C     SUFFIX AD REFERS TO SECTION OF CABLE FROM ANCHOR TO FIRST BUOY    000203
00260   C        (OR SHIP IF NO BUOYS)                                          000203
00260   C     SUFFIX EG REFERS TO SECTION OF CABLE FROM FIRST BUOY TO SECOND    000203
00260   C        BUOY (OR SHIP IF NO SECOND BUOY)                               000203
00260   C           (SET ALL PARAMETERS EQUAL TO ZERO IF NO BUOYS)              000203
00260   C     SUFFIX GT REFERS TO SECTION OF CABLE FROM SECOND BUOY TO SHIP     000203
00260   C        (SET ALL PARAMETERS EQUAL TO ZERO IF THERE ARE NO BUOYS OR ONE) 000203
00260   C                                                                       000203
00261         READ 20,SAD,EAD,WAD,DAD,DSAD                                      000215
00270         READ 20,SEG,EEG,WEG,DEG,DSEG                                      000226
00277         READ 20,SGT,EGT,WGT,DGT,DSGT                                      000237
00306      20 FORMAT(5F10.3)                                                    000250
00307         NCBC=0                                                            000250
```

```
   39 CONTINUE
      NCUC=NCRC+1
      EAU=EAU*144.
      EE*=EE**144.
      EGT=EGT*144.
C
C     30 PLOT TITLE
C
      READ 24,TITLE
C
C     G IS HORIZONTAL DISTANCE FROM SHIP TO ANCHOR IN FEET
C     H IS WATER DEPTH AT ANCHOR IN FEET
C     ICASE IS CASE NUMBER
C
      READ 25,G,H,ICASE
   25 FORMAT(2F10.2,I10)
C
C     WA IS FIRST BUOY WEIGHT IN LBS
C     WB IS SECOND BUOY WEIGHT IN LBS ( =0 IF NO BUOYS OR 1 BUOY)
C
      WA=(4./3.)*3.14159*RA**3*PA
      WB=(4./3.)*3.14159*RB**3*PB
C
C     RHOW IS DENSITY OF WATER IN SLUGS PER CUBIC FOOT
C     RHOA IS DENSITY OF AIR IN SLUGS PER CUBIC FOOT
C
      RHOW=1.998
      RHOA=0.00238
C
C     SPECIFY TENSION AND ANGLES ESTIMATE AND OTHER PARAMETERS AT ANCHOR
C
   31 CONTINUE
      TNSON1=64.4*((4./3.)*3.14159*((RA**3)+(RB**3)))-(WB+WA)
      IF(IBUOY.EQ.0) TNSON1=3000.0
      THETA1=0.
      PHI1=45.0*0.01745
C
C     SPECIFY INITIAL VALUES OF CONSTANTS
C
      HOOLD=1000.
      ZOLD=20000.
      YOLD=1000.
      ISHCT=1
      LTME=0
      LTM1=0
      LTM2=0
      YOLS=YOLD
      ZOLS=ZOLD
      ETA=10.*TNSON1
      LTEPA=0
      DELTO=TNSON1
      TPA=TNSON1
      THETPA=THETA1
      PHIPA=PHI1
      IIERTS=0
      IDELTA=0
      ETAU=ETA
```

```
00362           ITRTSS=0                                                    000372
00363           ISHF1=0                                                     000373
00364           ISHF2=0                                                     000374
00365           ISHFB=0                                                     000375
00366           IF(IBUOY.EQ.1.AND.IATCH1.EQ.1) ISHF1=1                      000376
00370           IF(IBUOY.EQ.2.AND.IATCH2.EQ.1) ISHF2=1                      000414
00372           IF(ISHF1.EQ.1.OR.ISHF2.EQ.1) ISHFB=1                        000432
00374        30 CONTINUE                                                    000451
00375           ITERTS=ITERTS+1                                             000451
00376           NUP=1                                                       000453
00376     C                                                                 000453
00376     C     CALCULATE TENSION AND CONFIGURATION ALONG CABLE FROM ANCHOR TO  000453
00376     C        FIRST BUOY (OR SHIP IF NO BUOYS)                         000453
00376     C                                                                 000453
00377           STHI=0                                                      000455
00400           SOI=0                                                       000456
00401           XI=0                                                        000457
00402           YI=0                                                        000460
00403           ZI=0                                                        000461
00404           SL=SAD                                                      000462
00405           XIX(1)=0.                                                   000464
00406           YIY(1)=0.                                                   000465
00407           ZIZ(1)=0.                                                   000466
00410           LMENT=2                                                     000467
00411           NSG1=3                                                      000471
00412           IF(IBUOY.EQ.0) NSG1=6                                       000473
00414           CALL CONFIG(EAD,DAD,DSAD,WAD,H,STHI,SOI,XI,YI,ZI,THSONI,THETAI,PHI  000477
00414          1I,SL,RHOW,NUP,SF,SIF,XF,YF,ZF,TF,THETAF,PHIF,SS,SIS,XS,YS,ZS,TS,TH  000477
00414          2ETAS,PHIS,VCS,THETVS,LS,CX,D,THEC,CZ,CD,NSG1,XIX,YIY,ZIZ,LMENT,DLI  000477
00414     C                                                                 000477
00414     C     CHECK TO SEE IF THERE IS AT LEAST ONE BUOY                  000477
00414     C                                                                 000477
00415           IF(IBUOY.EQ.0) GO TO 491                                    000557
00417           IF(ISHF1.EQ.1) GO TO 491                                    000561
00417     C                                                                 000561
00417     C                                                                 000561
00417     C     CALCULATE TENSION,ANGLES,AND POSITION OF FIRST BUOY         000561
00417     C                                                                 000561
00421           CALL SUBSHF(IRROR,NUP,WA,RA,RHOW,TF,THETAF,PHIF,XF,YF,ZF,G,T,ROC,T  000564
00421          1G,THETAG,PHIG,XG,YG,ZG,CX,D,THEC,CZ,CB)                     000564
00422           IF(IRROR.EQ.0) GO TO 48                                     000617
00424           PRINT 46                                                    000621
00426        46 FORMAT(1H1,'SUBSURFACE BUOY CALCULATIONS ARE NOT WORKING')  000625
00427           GO TO  999                                                  000625
00430        48 CONTINUE                                                    000627
00430     C                                                                 000627
00430     C     CALCULATE TENSION AND CONFIGURATION ALONG CABLE FROM FIRST BUOY  000627
00430     C        TO SECOND BUOY (OR SHIP IF NO SECOND BUOY)               000627
00430     C                                                                 000627
00431           NUP=1                                                       000627
00432           SL=SEG                                                      000630
00433           NSG2=1                                                      000632
00434           IF(IBUOY.EQ.1) NSG2=3                                       000633
00436           CALL CONFIG(EEG,DEG,DSEG,WEG,H,SF,SIF,XG,YG,ZG,TG,THETAG,PHIG,SL,R  000640
00436          1HOW,NUP,SH,SIH,XH,YH,ZH,TH,THETAH,PHIH,ST,SIT,XT,YT,ZT,TT,THETAT,P  000640
00436          2HIT,VCT,THETVT,LT,CX,D,THEC,CZ,CD,NSG2,XIX,YIY,ZIZ,LMENT,DLI)  000640
00437           ZOLD=ZH                                                     000720
```

```
00440            IF(ISHF1.EQ.0) GO TO 49                                             000722
00442            ITRTSS=ITRTSS+1                                                     000724
00443         49 CONTINUE                                                            000730
00444            ZOF=ABS(ZH-H)                                                       000730
00444      C                                                                         000730
00444      C                                                                         000730
00444      C     CHECK IF THERE ARE TWO BUOYS                                        000730
00444      C                                                                         000730
00445            IF(IBUOY.EQ.0.OR.IBUOY.EQ.1) GO TO 492                              000733
00445      C                                                                         000733
00445      C     CALCULATE THE TENSION,ANGLES,AND POSITION OF SECOND BUOY            000733
00445      C                                                                         000733
00447            CALL SUBSHF(IRROR,NUP,+U,RB,RHOW,TH,THETAH,PHIH,XH,YH,ZH,G,H,RHE,T  000745
00447           1I1,THETI1,PHII1,XI1,YI1,ZI1,CX,D,THEC,CZ,CB)                        000745
00450            IF(IRROR.EQ.0) GO TO 58                                             001000
00452            PRINT 46                                                            001002
00454            GO TO 999                                                           001006
00455         58 CONTINUE                                                            001010
00455      C                                                                         001010
00455      C     CALCULATE TENSION AND CONFIGURATION ALONG CABLE FROM SECOND BUOY    001010
00455      C        TO SHIP                                                          001010
00455      C                                                                         001010
00456            NUP=1                                                               001010
00457            SL=SGT                                                              001011
00460            NSG3=2                                                              001013
00461            CALL CONFIG(EGT,DGT,DSGT,WGT,H,SH,SIH,XI1,YI1,ZI1,TI1,THETI1,PHII1  001015
00461           1,SL,RHOW,NUP,SJ,SIJ,XJ,YJ,ZJ,TJ,THETAJ,PHIJ,SU,SIU,XU,YU,ZU,TU,THE  001015
00461           2TAU,PHIU,VCU,THETVU,LU,CX,D,THEC,CZ,CB,NSG3,XIX,YIY,ZIZ,LMENT,DL)   001015
00462            ZOLD=ZJ                                                             001075
00463            IF(ISHF2.EQ.0) GO TO 59                                             001077
00465            ITRTSS=ITRTSS+1                                                     001101
00466         59 CONTINUE                                                            001105
00467            ZOG=ABS(ZJ-H)                                                       001105
00467      C                                                                         001105
00470            GO TO 493                                                           001110
00471        491 CONTINUE                                                            001112
00472            SJ=SF                                                               001112
00473            SIJ=SIF                                                             001113
00474            XJ=XF                                                               001115
00475            YJ=YF                                                               001117
00476            ZJ=ZF                                                               001121
00477            TJ=TF                                                               001123
00500            THETAJ=THETAF                                                       001125
00501            PHIJ=PHIF                                                           001127
00502            GO TO 493                                                           001131
00503        492 CONTINUE                                                            001133
00504            SJ=SH                                                               001133
00505            SIJ=SIH                                                             001134
00506            XJ=XH                                                               001136
00507            YJ=YH                                                               001140
00510            ZJ=ZH                                                               001142
00511            TJ=TH                                                               001144
00512            THETAJ=THETAH                                                       001146
00513            PHIJ=PHIH                                                           001150
00514        493 CONTINUE                                                            001153
00515            HM1A=H-1.2*HA                                                       001153
00516            HM2A=H-1.2*HB                                                       001157
```

```
00517         IF(ISHF1.EQ.1) H=HH1A                                      001164
00521         IF(ISHF2.EQ.1) H=HH2A                                      001171
00523         ERS=SQRT((XJ)**2+(YJ-G)**2+(ZJ-H)**2)                      001201
00524         HH1B=HH1A+1.2*HA                                           001217
00525         HH2B=HH2A+1.2*HB                                           001222
00526         IF(ISRF1.EQ.1) H=HH1B                                      001225
00530         IF(ISHF2.EQ.1) H=HH2B                                      001232
00532         TOLD=YJ                                                    001237
00533         ZOLD=ZJ                                                    001241
00534         IF(ERS.LE.EPSLNA) GO TO 550                                001243
00536         IF(ERS.GT.200000.) GO TO 550                               001247
00540         IF(ITERTS.GE.NOITER) GO TO 550                             001251
00540   C                                                                001253
00540   C     CORRECT TENSION AND ANGLES AT ANCHOR                       001253
00540   C                                                                001253
00542         HH1A=H-1.2*HA                                              001257
00543         HH2A=H-1.2*HB                                              001262
00544         IF(ISHF1.EQ.1) H=HH1A                                      001265
00546         IF(ISHF2.EQ.1) H=HH2A                                      001272
00550         CALL TENCOR(EPSLNA,G,H,ETA,DELTO,TPA,THETPA,PHIPA,XJ,YJ,ZJ,TW,THET 001277
00550        1AW,PHIW,ETAN,DELTN,LTEPA,ITERTS)                           001277
00551         HH1B=HH1A+1.2*HA                                           001323
00552         HH2B=HH2A+1.2*HB                                           001326
00553         IF(ISHF1.EQ.1) H=HH1B                                      001331
00555         IF(ISHF2.EQ.1) H=HH2B                                      001336
00557         ETA=ETAN                                                   001343
00560         DELTO=DELTN                                                001345
00561         TPA=TW                                                     001347
00562         THETPA=THETAW                                              001351
00563         PHIPA=PHIW                                                 001353
00564         TNSON1=TW                                                  001355
00565         THETA1=THETAW                                              001356
00566         PHI1=PHIW                                                  001357
00567         GO TO 30                                                   001360
00570     550 CONTINUE                                                   001362
00571     560 CONTINUE                                                   001362
00571   C                                                                001362
00571   C                                                                001362
00571   C                                                                001362
00571   C                                                                001362
00571   C                                                                001362
00571   C                                                                001362
00571   C     PRINTED OUTPUT                                             001362
00571   C                                                                001362
00571   C                                                                001362
00572         EAD=EAU/144.                                               001362
00573         EEG=EEG/144.                                               001364
00574         EGT=EGT/144.                                               001367
00576         PRINT 109,ICASE                                            001372
00600     109 FORMAT(1H1,'CASE NUMBER',I4)                               001377
00601         IF(IBUOY.EQ.0) GO TO 111                                   001377
00603         PRINT 110                                                  001401
00605     110 FORMAT(1H ,'PARAMETERS OF CABLE FROM ANCHOR TO FIRST BUOY')  001405
00606         GO TO 113                                                  001405
00607     111 CONTINUE                                                   001407
00610         PRINT 112                                                  001407
00612     112 FORMAT(1H ,'PARAMETERS OF CABLE FROM ANCHOR TO SHIP')      001413
```

```
00613        113 CONTINUE                                                              001413
00614            PRINT 120,SAD,LAD,WAD,DAD,DSAD                                        001413
00623        120 FORMAT(1H ,'LENGTH=',F8.1,' FEET    E=',E8.4,' PSI    WT PER FT=',    001423
00623           1F8.5,' LBS    CD=',F8.4,' INCHES    STR MEM DIAM=',F8.4,' INCHES')    001423
00624            IF(IBUOY.EQ.0) GO TO 195                                              001423
00626            IF(IBUOY.EQ.1) GO TO 161                                              001425
00630            PRINT 160                                                             001430
00632        160 FORMAT(//1H ,'PARAMETERS OF CABLE FROM FIRST BUOY TO SECOND BUOY')    001434
00633            GO TO 163                                                             001434
00634        161 CONTINUE                                                              001436
00635            PRINT 162                                                             001436
00637        162 FORMAT(//1H ,'PARAMETERS OF CABLE FROM FIRST BUOY TO SHIP')           001442
00640        163 CONTINUE                                                              001442
00641            PRINT 120,SEG,LEG,WEG,DEG,DSEG                                        001442
00650            IF(IBUOY.EQ.1) GO TO 195                                              001452
00652            PRINT 170                                                             001455
00654        170 FORMAT(//1H ,'PARAMETERS OF CABLE FROM SECOND BUOY TO SHIP')          001461
00655            PRINT 120,SGT,LGT,WGT,DGT,DSGT                                        001461
00655       C                                                                          001461
00664        195 CONTINUE                                                              001473
00665            PRINT 176                                                             001473
00667        176 FORMAT(//)                                                            001476
00670            ESN=ERS                                                               001476
00671            IF(ISHF1.EQ.1) ERS=ZOF                                                001500
00673            IF(ISHF2.EQ.1) ERS=ZOG                                                001505
00675            PRINT 180,ERS                                                         001516
00700        180 FORMAT(//1H ,'POSITION OF SHIP IS ACCURATE TO ',F6.1,' FEET')         001523
00701            ERS=ESN                                                               001523
00702            PRINT 176                                                             001525
00704            IF(IBUOY.EQ.0) GO TO 230                                              001531
00706            PRINT 210                                                             001533
00710        210 FORMAT(//1H ,'PARAMETERS OF FIRST SPHERICAL BUOY')                    001537
00711            PRINT 212                                                             001537
00713        212 FORMAT(1H0,36X,'(SUBSURFACE BUOY)')                                   001543
00714            ZSLS=H-ZS(LS)                                                         001543
00715            PRINT 226,EA,ZSLS                                                     001547
00721        226 FORMAT(1H ,'EXCESS BUOYANCY=',F8.1,' POUNDS     BUOY DEPTH=',F10.1    001555
00721           1,' FEET')                                                             001555
00722            PRINT 220,RA,WA,PA                                                    001555
00727        220 FORMAT(1H ,'RADIUS=',F7.2,' FEET     WEIGHT=',F8.1,' POUNDS     DEN   001564
00727           1SITY=',F7.2,' LBS PER CUB FT')                                        001564
00730            DMA=2.*RA                                                             001564
00731            IF(IBUOY.EQ.1) GO TO 230                                              001567
00733            PRINT 240                                                             001572
00735        240 FORMAT(//1H ,'PARAMETERS OF SECOND SPHERICAL BUOY')                   001576
00736            PRINT 212                                                             001576
00740            ZTLT=H-ZT(LT)                                                         001602
00741            PRINT 226,EB,ZTLT                                                     001606
00745            PRINT 220,RB,WB,PB                                                    001614
00752            DMB=2.*RB                                                             001623
00753            IF(LTM2.EQ.1) GO TO 243                                               001626
00755            GO TO 244                                                             001631
00756        243 CONTINUE                                                              001633
00757        244 CONTINUE                                                              001633
00760            PRINT 176                                                             001633
00762        230 CONTINUE                                                              001637
00763            GG=G                                                                  001637
```

```
      IF(ISHF1.EQ.1) GO TO 261
      IF(ISHF2.EQ.1) GO TO 262
      GO TO 263
  261 CONTINUE
      G=SQRT((XT(LT))**2+(YT(LT))**2)
      GO TO 263
  262 CONTINUE
      G=SQRT((XU(LU))**2+(YU(LU))**2)
  263 CONTINUE
      PRINT 250,G
      G=GG
  250 FORMAT(//1H ,'HORIZONTAL DISTANCE FROM ANCHOR TO SHIP =',F9.1,' FE
     1ET')
      PRINT 260,H
  260 FORMAT(1H ,'WATER DEPTH AT ANCHOR=',F9.1,' FEET')
      PRINT 270,ITERTS
  270 FORMAT(///1H ,'NUMBER OF ITERATIONS =',I3)
      PRINT 280,DELIN
  280 FORMAT(1H ,'DELTA OF ITERATION PROCESS=',F12.3,' AT ANCHOR')
      PRINT 176
C
  342 CONTINUE
      PRINT 350
  350 FORMAT(1H1,'ALL LENGTHS ARE FEET,TENSION IS LBS,ANGLES ARE DEGREES
     1,AND CURRENT IS KNOTS')
      PRINT 176
      PRINT 176
      PRINT 360
  360 FORMAT(5X,'LENGTH',3X,'ELONG LNTH',3X,'PCT ELONG',8X,'X',11X,'Y',1
     11X,'Z',8X,'TENSION',7X,'THETA',8X,'PHI',6X,'CURRENT',5X,'CUR DIR')
      PRINT 361
  361 FORMAT(///1H ,61X,'ANCHOR'/)
C     PERELG IS PERCENT ELONGATION OF THE CABLE((TOTAL ELONGATED LENGTH
C        MINUS TOTAL UNSTRETCHED LENGTH) DIVIDED BY UNSTRETCHED LENGTH)
      DO 370 N=1,LS
      PERELG=0.
      IF(SIS(N).EQ.0.) GO TO 362
      PERELG=(SS(N)-SIS(N))/SIS(N)
  362 CONTINUE
      PRINT 380,SIS(N),SS(N),PERELG,XS(N),YS(N),ZS(N),TS(N),THETAS(N),PH
     1IS(N),VCS(N),THETVS(N)
  370 CONTINUE
  380 FORMAT(2F12.1,F12.3,4F12.1,4F12.2)
      IF(IBUOY.EQ.0) GO TO 421
      PRINT 390
  390 FORMAT(/60X,'FIRST BUOY'/)
      DO 400 N=1,LT
      PERELG=(ST(N)-SIT(N))/SIT(N)
      PRINT 380,SIT(N),ST(N),PERELG,XT(N),YT(N),ZT(N),TT(N),THETAT(N),PH
     1IT(N),VCT(N),THETVT(N)
  400 CONTINUE
      IF(IBUOY.EQ.1) GO TO 421
      PRINT 410
  410 FORMAT(/59X,'SECOND BUOY'/)
      DO 422 N=1,LU
      PERELG=(SU(N)-SIU(N))/SIU(N)
      PRINT 380,SIU(N),SU(N),PERELG,XU(N),YU(N),ZU(N),TU(N),THETAU(N),PH
```

```
01131        IIU(N),VCU(N),THET,U(N)                                    002067
01146    420 CONTINUE                                                   002110
01150    441 CONTINUE                                                   002110
01151        PRINT 430                                                  002110
01153    430 FORMAT(/62X,'SHIP')                                        002113
01154        IF(IPLOT.EQ.0) GO TO 999                                   002113
01156        PRINT 419                                                  002115
01160    419 FORMAT(1H1)                                                002121
01160  C                                                                002121
01160  C     3D PLOT OF POSITION OF SYSTEM                              002121
01160  C                                                                002121
01161        CALL MODE3D(P,0)                                           002121
01162        CALL SETSMG(P,93,0.)                                       002125
01163        CALL BEGINS(PLOT)                                          002132
01164        PLOT(1)=-4000.                                             002135
01165        PLOT(2)=14000.                                             002137
01166        PLOT(3)=0.                                                 002141
01167        PLOT(4)=18000.                                             002142
01170        PLOT(5)=0.                                                 002144
01171        PLOT(6)=18000.                                             002145
01172        PLOT(9)=0.                                                 002146
01173        PLOT(25)=2.                                                002147
01174        PLOT(26)=2.                                                002151
01175        PLOT(29)=1.                                                002152
01176        PLOT(30)=1.                                                002154
01177        PLOT(31)=1.                                                002155
01200        PLOT(32)=1.                                                002156
01201        CALL SETSMG(P,14,0.)                                       002157
01202        CALL OBJCTG(P,200.,200.,3600.,2900.)                       002164
01203        CALL SUBJ3D (P,PLOT)                                       002173
01204        CALL GRPH3D(P,PLOT,XS,YS,ZS,LS,6,XCHAR,6,YCHAR,6,ZCHAR,6,TITLE)  002177
01205        IF(IBUOY.EQ.0) GO TO 510                                   002217
01207        CALL PNT3D(P,PLOT,XT,YT,ZT,LT)                             002221
01210        CALL SHDE3D(P,PLOT,LT,XT,YT,ZT,1,0)                        002231
01211        IF(IBUOY.EQ.1) GO TO 510                                   002243
01212        CALL PNT3D(P,PLOT,XU,YU,ZU,LU)                             002246
01214        CALL SHDE3D(P,PLOT,LU,XU,YU,ZU,1,0)                        002256
01215    510 CONTINUE                                                   002271
01216        CALL PAGEG(P,0,1,1)                                        002271
01216  C                                                                002271
01216  C     OTHER PLOTS                                                002271
01216  C                                                                002271
01217        XMIN=0.                                                    002276
01220        YMIN=0.                                                    002277
01221        ZMIN=0.                                                    002300
01222        XMAX=1.                                                    002301
01223        YMAX=1.                                                    002303
01224        ZMAX=1.                                                    002304
01225        DO 630 N=1,LS                                              002320
01230        IF(XS(N).LT.XMIN) XMIN=XS(N)                               002320
01232        IF(XS(N).GE.XMAX) XMAX=XS(N)                               002325
01234        IF(YS(N).GE.YMAX) YMAX=YS(N)                               002333
01236        IF(ZS(N).GE.ZMAX) ZMAX=ZS(N)                               002341
01240    630 CONTINUE                                                   002351
01242        IF(IBUOY.EQ.0) GO TO 660                                   002351
01244        DO 640 N=1,LT                                              002356
01247        IF(XT(N).LT.XMIN) XMIN=XT(N)                               002356
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01251          IF(XT(N).GE.XMAX) XMAX=XT(N)                          002363
01253          IF(YT(N).GE.YMAX) YMAX=YT(N)                          002371
01255          IF(ZT(N).GE.ZMAX) ZMAX=ZT(N)                          002377
01257      640 CONTINUE                                              002407
01261          IF(IBUOY.EQ.1) GO TO 660                              002407
01263          DO 650 N=1,LU                                         002415
01266          IF(XU(N).LE.XMIN) XMIN=XU(N)                          002415
01270          IF(XU(N).GE.XMAX) XMAX=XU(N)                          002422
01272          IF(YU(N).GE.YMAX) YMAX=YU(N)                          002430
01274          IF(ZU(N).GE.ZMAX) ZMAX=ZU(N)                          002436
01276      650 CONTINUE                                              002447
01300      660 CONTINUE                                              002447
01301          CALL SUBJEG(P,XMIN,YMIN,XMAX,YMAX)                    002447
01302          CALL GRAPHG(P,0,XS,YS,6,XCHAR,6,YCHAR,6,TITLE)        002455
01303          CALL POINTG(P,LS,XS,YS)                               002471
01304          CALL LINESG(P,LS,XS,YS)                               002477
01305          IF(IBUOY.EQ.0) GO TO 600                              002505
01307          CALL POINTG(P,LT,XT,YT)                               002507
01310          CALL LINESG(P,LT,XT,YT)                               002515
01311          IF(IBUOY.EQ.1) GO TO 600                              002523
01313          CALL POINTG(P,LU,XU,YU)                               002526
01314          CALL LINESG(P,LU,XU,YU)                               002534
01315      600 CONTINUE                                              002543
01316          CALL PAGEG(P,0,1,1)                                   002543
01317          CALL SUBJEG(P,YMIN,ZMIN,YMAX,ZMAX)                    002550
01320          CALL GRAPHG(P,0,YS,ZS,6,YCHAR,6,ZCHAR,6,TITLE)        002557
01321          CALL POINTG(P,LS,YS,ZS)                               002573
01322          CALL LINESG(P,LS,YS,ZS)                               002601
01323          IF(IBUOY.EQ.0) GO TO 610                              002607
01325          CALL POINTG(P,LT,YT,ZT)                               002611
01326          CALL LINESG(P,LT,YT,ZT)                               002617
01327          IF(IBUOY.EQ.1) GO TO 610                              002625
01331          CALL POINTG(P,LU,YU,ZU)                               002630
01332          CALL LINESG(P,LU,YU,ZU)                               002636
01333      610 CONTINUE                                              002645
01334          CALL PAGEG(P,0,1,1)                                   002645
01335          CALL SUBJEG(P,XMIN,ZMIN,XMAX,ZMAX)                    002652
01336          CALL GRAPHG(P,0,XS,ZS,6,XCHAR,6,ZCHAR,6,TITLE)        002661
01337          CALL POINTG(P,LS,XS,ZS)                               002675
01340          CALL LINESG(P,LS,XS,ZS)                               002703
01341          IF(IBUOY.EQ.0) GO TO 620                              002711
01343          CALL POINTG(P,LT,XT,ZT)                               002713
01344          CALL LINESG(P,LT,XT,ZT)                               002721
01345          IF(IBUOY.EQ.1) GO TO 620                              002727
01347          CALL POINTG(P,LU,XU,ZU)                               002732
01350          CALL LINESG(P,LU,XU,ZU)                               002740
01351      620 CONTINUE                                              002747
01352          CALL PAGEG(P,0,1,1)                                   002747
01353          CALL EXITG(P)                                         002754
01354      999 CONTINUE                                              002760
01354    C                                                           002760
01354    C                                                           002760
01354    C                                                           002760
01354    C     DYNAMIC SIMULATION IF IDYMIC=1                        002760
01354    C                                                           002760
01355          IF(IDYMIC.NE.1) GO TO 1100                            002760
01357          DO 1030 N=1,NSGI                                      003022
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01362        DS(N)=USAD/12.                                                    003022
01363        DOUT(N)=DAD/12.                                                   003023
01364        ECB(N)=EAD*144.                                                   003025
01365        WCB(N)=WAD                                                        003027
01366   1000 CONTINUE                                                          003032
01370        IF(IBUOY.EQ.0) GO TO 1030                                         003032
01372        NB=NSG1+1                                                         003034
01373        NE=NSG1+NSG2                                                      003037
01374        DO 1010 N=NB,NE                                                   003042
01377        DS(N)=USEG/12.                                                    003047
01400        DOUT(N)=DEG/12.                                                   003050
01401        ECB(N)=EEG*144.                                                   003052
01402        WCB(N)=WEG                                                        003054
01403   1010 CONTINUE                                                          003057
01405        IF(IBUOY.EQ.1) GO TO 1030                                         003057
01407        NB3=NE+1                                                          003062
01410        NE3=NE+NSG3                                                       003065
01411        DO 1020 N=NB3,NE3                                                 003070
01414        DS(N)=USGT/12.                                                    003075
01415        DOUT(N)=DGT/12.                                                   003076
01416        ECB(N)=EGT*144.                                                   003100
01417        WCB(N)=WGT                                                        003102
01420   1020 CONTINUE                                                          003110
01422   1030 CONTINUE                                                          003110
01423        DO 1040 N=1,6                                                     003110
01426        RAD(N)=0.                                                         003110
01427        EXB(N)=0.                                                         003110
01430        WT(N)=0.                                                          003111
01431   1040 CONTINUE                                                          003113
01433        IF(IBUOY.EQ.0) GO TO 1050                                         003113
01435        RAD(4)=RA                                                         003115
01436        EXB(4)=EA                                                         003117
01437        WT(4)=WA                                                          003121
01440        IF(IBUOY.EQ.1) GO TO 1050                                         003123
01442        RAD(5)=RB                                                         003126
01443        EXB(5)=EB                                                         003130
01444        WT(5)=WB                                                          003132
01445   1050 CONTINUE                                                          003135
01446        CALL DYMICS(XIX,YIY,ZIZ,DS,ECB,DL,G,H,CX,CZ,CD,D,THEC,            003135
01446       1DOUT,RHOW,WCB,IBUOY,RAD,EXB,WT,TMMAX,XCHAR,YCHAR,ZCHAR,XCHRR      003135
01446       2,YCHRR,ZCHRR,VELX,VELY,VELZ,TEN,TIM,TITLE,IPLOT,AMPX,AMPZ,OMEGAX, 003135
01446       3OMEGAZ,PHANGX,PHANGZ)                                             003135
01447   1100 CONTINUE                                                          003207
01447 C                                                                        003207
01447 C      GO BACK TO BEGINNING OF PROGRAM TO READ IN NEW VALUES FOR NEXT    003207
01447 C         CASE OR END PROGRAM                                            003207
01447 C                                                                        003207
01450        IF(NCBC.LT.NCB) GO TO 39                                          003207
01452        IF(NCDC.LT.NCD) GO TO 38                                          003212
01454        IF(NCEC.LT.NCE) GO TO 28                                          003216
01456        STOP                                                              003222
01457        END                                                               003226

   END OF COMPILATION:        NO  DIAGNOSTICS.
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@FOR,SI CONFIG,CONFIG
FOR E12B-01/11/77-04:57:16 (,0)

   SUBROUTINE CONFIG    ENTRY POINT 001277

   STORAGE USED: CODE(1) 001467; DATA(0) 000321; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   RUNGE
    0004   ANGLE
    0005   EXP
    0006   COS
    0007   SIN
    0010   NERR2$
    0011   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0001    000104 100L     0001    000107 110L     0001    000737 120L     0001    000771 130L     0001    001107 18L
    0001    000243 19L      0001    000247 20L      0001    000255 30L      0001    000652 40L      0001    000172 49L
    0001    000172 50L      0001    000161 60L      0001    001031 64L      0001    000164 70L      0001    000166 80L
    0001    001221 90L      0000 R  000137 B        0000 R  000152 CDN      0000 R  000147 CDN1     0000 R  000150 CDN2
    0000 R  000151 CDN3     0000 R  000154 CDT      0000 R  000153 CDT1     0000 R  000163 CDOS     0000 R  000052 D
    0000 R  000165 DS       0000 R  000166 DX       0000 R  000167 DY       0000 R  000170 DZ       0000 I  000136 IC
    0000 I  000130 IKEEP    0000    000223 INJP$    0000 I  000142 K        0000 I  000141 M        0000 I  000140 N
    0000 R  000000 R        0000 R  000146 RE       0000 R  000132 S        0000 R  000124 SEG      0000 R  000127 SLL
    0000 R  000125 STEST    0000 R  000131 STR      0000 R  000155 U        0000 R  000160 UCC      0000 R  000156 V
    0000 R  000145 VC       0000 R  000161 VCC      0000 R  000157 W        0000 R  000162 WCC      0000 R  000164 WCCA
    0000 R  000126 WCCC     0000 R  000133 X        0000 R  000134 Y        0000 R  000135 Z        0000 R  000143 ZAP
    0000 R  000144 ZAPR


 00101           SUBROUTINE CONFIG(E,DM,DD,WC H,S1,SO1,X1,Y1,Z1,T1,TH1,PHI1,SL,RHOW          000063
 00101          1,NUP,SF,SIF,XF,YF,ZF,TF,THF,PHIF,SS,SIS,XS,YS,ZS,TS,THS,PHIS,VCS,T          000063
 00101          2HCS,L,CXX,UXX,THEC,CZZ,CB,NSEG,X1X,Y1Y,Z1Z,LMENT,DL)                        000063
 00103           DIMENSION SS(30),SIS(30),XS(30),YS(30),ZS(30),TS(30),THS(30),PHIS(          000063
 00103          130),VCS(30),THCS(30),R(42) C(42),X1X(7),Y1Y(7),Z1Z(7),UL(6)                 000063
 00103     C                                                                                 000063
 00103     C     INITIAL VALUES OF PARAMETERS                                                000063
 00103     C                                                                                 000063
 00104           SEG=NSEG                                                                    000063
 00105           STEST=SO1+SL/SEG                                                            000066
 00106           WCCC=WC                                                                     000072
 00107           IF(NUP.EQ.2) GO TO 100                                                      000074
 00111           SLL=SO1+SL                                                                  000077
 00112           GO TO 110                                                                   000102
 00113       100 CONTINUE                                                                    000104
 00114           SLL=SO1-SL                                                                  000104
 00115       110 CONTINUE                                                                    000107
 00116           L=2                                                                         000107
```

```
00117          IKELP=0                                              000110
00120          SS(1)=S1                                             000111
00121          SIS(1)=SO1                                           000113
00122          XS(1)=X1                                             000115
00123          YS(1)=Y1                                             000117
00124          ZS(1)=Z1                                             000121
00125          TS(1)=T1                                             000123
00126          THS(1)=TH1/C.01745                                   000125
00127          PHIS(1)=PHI1/0.01745                                 000130
00130          STR=S1                                               000133
00131          S=SO1                                                000134
00132          X=X1                                                 000135
00133          Y=Y1                                                 000136
00134          Z=Z1                                                 000137
00135          R(1)=T1                                              000140
00136          R(2)=TH1                                             000141
00137          R(3)=PHI1                                            000143
00140          IC=0                                                 000145
00140    C                                                          000145
00140    C      CONVERT DM AND DD FROM INCHES TO FEET               000145
00140    C                                                          000145
00141          DM=DM/12.                                            000146
00142          DD=DD/12.                                            000151
00142    C                                                          000151
00142    C     CONSTANTS FOR SUBROUTINE RUNGE                       000151
00142    C                                                          000151
00143          IF(NOP.EQ.1) GO TO 60                                000154
00145          GO TO 70                                             000157
00146       60 CONTINUE                                             000161
00147          B=20.0                                               000161
00150          GO TO 80                                             000162
00151       70 CONTINUE                                             000164
00152          B=-20.0                                              000164
00153       80 CONTINUE                                             000166
00154          N=3                                                  000166
00155          M=0                                                  000167
00156          K=0                                                  000170
00157       49 CONTINUE                                             000172
00160       50 CONTINUE                                             000172
00160    C                                                          000172
00160    C     CALCULATE CURRENT MAGNITUDE AND DIRECTION            000172
00160    C                                                          000172
00161          ZAP=H-Z                                              000172
00162          IF(ZAP.GE.DXX) ZAP=DXX                               000175
00164          ZAPM=-ZAP*CZZ                                        000203
00165          ZAP=H-Z                                              000206
00166          IF(Z.GT.H) ZAPM=0.                                   000210
00170          VC=(CXX*EXP(ZAPM))*1.689                             000220
00171          IF(ZAP.LE.DXX) GO TO 19                              000226
00173          VC=CB*1.689+(Z/(H-DXX))*(VC-CD*1.689)                000232
00174       19 CONTINUE                                             000243
00175          IF(Z.EQ.Z1) GO TO 20                                 000243
00177          GO TO 30                                             000245
00200       20 CONTINUE                                             000247
00201          VCS(1)=VC/1.689                                      000247
00202          THCS(1)=THEC/0.01745                                 000251
00203       30 CONTINUE                                             000255
```

```
00203   C                                                                        000255
00203   C      SPECIFY OR CALCULATE NORMAL AND TANGENTIAL DRAG COEFFICIENTS     000255
00203   C         FOR CABLE                                                     000255
00203   C      RE IS REYNOLDS NUMBER                                            000255
00203   C                                                                        000255
00204          RE=VC*DM/1.6E-5                                                   000255
00205          CON1=1.2*(EXP(-((RE-2.0E2)/R.0E3)))                               000260
00206          CON2=0.9*(EXP((RE-2.5E3)/4.3E4))                                  000270
00207          CON3=1.2                                                          000301
00210          IF(RE.GE.2.0E2.AND.RE.LT.2.5E3) CDN=CON1                          000303
00212          IF(RE.GE.2.5E3.AND.RE.LT.1.5E4) CDN=CON2                          000323
00214          IF(RE.GE.1.5E4.AND.RE.LT.2.0E5) CDN=CON3                          000371
00216          CDT1=0.006*(EXP(-((RE-2.0E3)/2.2E5)))                             000411
00217          IF(RE.GE.2.0E3.AND.RE.LE.2.0E5) CDT=CDT1                          000422
00217   C                                                                        000422
00217   C      CALCULATE CURRENT COMPONENTS IN INERTIAL COORDINATES             000422
00217   C                                                                        000422
00221          U=-VC*SIN(THEC)                                                   000446
00222          V=VC*COS(THEC)                                                    000453
00223          W=0.                                                              000460
00223   C                                                                        000460
00223   C      CALCULATE CURRENT COMPONENTS IN CABLE COORDINATES                000460
00223   C                                                                        000460
00224          UCC=U*COS(R(2))+V*SIN(R(2))                                       000461
00225          VCC=-U*SIN(R(2))*COS(R(3))+V*COS(R(2))*COS(R(3))+W*SIN(R(3))      000466
00226          WCC=U*SIN(R(2))*SIN(R(3))-V*COS(R(2))*SIN(R(3))+W*COS(R(3))       000503
00226   C                                                                        000503
00226   C      STEADY STATE EQUATIONS                                           000503
00226   C                                                                        000503
00227          IF(R(1).EQ.0.) R(1)=1.                                            000514
00231          COOS=COS(R(3))                                                    000520
00232          IF(COOS.EQ.0.) COOS=0.0001                                        000524
00234          WCCA=WC+(64.4*3.14159*((DM/12.)**2)/4.))                          000530
00235          IF(Z.GE.H) WC=WCCA                                                000536
00237          IF(Z.LE.0.) WC=0.                                                 000544
00241          IF(Z.GT.0..AND.Z.LT.H) WC=WCCC                                    000550
00243          D(1)=WC*SIN(R(3))-0.5*RHOW*3.14159*DM*CDT*VCC*ABS(VCC)            000567
00244          D(2)=0.5*RHOW*DM*CDN*UCC*ABS(UCC)/(R(1)*COOS)                     000605
00245          D(3)=(WC*COS(R(3))-0.5*RHOW*DM*CDN*WCC*ABS(WCC))/R(1)             000615
00245   C                                                                        000615
00245   C       SOLVE ABOVE SIMULTANEOUS DIFFERENTIAL EQUATIONS                 000615
00245   C                                                                        000615
00246          CALL RUNGE(N,R,D,S,H,M,K)                                         000631
00247          GO TO (50,40),K                                                   000642
00250       40 CONTINUE                                                          000652
00250   C                                                                        000652
00250   C      CALCULATE COMPONENTS OF ELEMENT AND STRETCH                      000652
00250   C                                                                        000652
00251          IF(R(1).LE.0.) R(1)=0.                                            000652
00253          DS=D*(1.+(4.*R(1))/(3.14159*(DD**2)*E))                           000655
00254          STR=STR+DS                                                        000667
00255          DX=-DS*SIN(R(2))*COS(R(3))                                        000671
00256          DY=DS*COS(R(2))*COS(R(3))                                         000703
00257          DZ=DS*SIN(R(3))                                                   000711
00257   C                                                                        000711
00257   C      CALCULATE NEW COORDINATES                                        000711
00257   C                                                                        000711
```

```
      X=X+DX                                                         000716
      Y=Y+DY                                                         000721
      Z=Z+DZ                                                         000724
C                                                                    000724
C     IC IS A COUNTER SO THAT THE COORDINATES AND TENSION WIL. SE    000724
C        STORED ONLY AT SPECIFIC INTERVALS                           000724
C                                                                    000724
      IF(S.GE.SLL) GO TO 120                                         000726
      IF(S.LT.STEST) GO TO 130                                       000732
  120 CONTINUE                                                       000737
      XIX(LMENT)=X                                                   000737
      YIY(LMENT)=Y                                                   000742
      ZIZ(LMENT)=Z                                                   000746
      DL(LMENT-1)=S-SO1                                              000752
      SO1=S                                                          000757
      STEST=S+SL/SEG                                                 000761
      LMENT=LMENT+1                                                  000765
  130 CONTINUE                                                       000771
      IC=IC+1                                                        000771
      IF(S.GE.SLL.AND.NUP.EQ.1) GO TO 64                             000773
      IF(S.LE.SLL.AND.NUP.EQ.2) GO TO 64                             001010
      IF(IC.LT.50) GO TO 49                                          001025
   64 CONTINUE                                                       001031
      CALL ANGLE(R(2),R(3),1)                                        001031
C                                                                    001031
      ZAP=H-Z                                                        001035
      IF(ZAP.GE.CXX) ZAP=DXX                                         001041
      ZAPM=-ZAP*CZZ                                                  001047
      ZAP=H-Z                                                        001052
      IF(Z.GT.H) ZAPM=0.                                             001054
      VC=(CXX*EXP(ZAPM))*1.689                                       001064
      IF(ZAP.LE.DXX) GO TO 18                                        001072
      VC=CB*1.689+(Z/(H-DXX))*(VC-CB*1.689)                          001076
   18 CONTINUE                                                       001107
      IC=0                                                           001107
C                                                                    001107
      SS(L)=STR                                                      001107
      SIS(L)=S                                                       001113
      XS(L)=X                                                        001117
      YS(L)=Y                                                        001123
      ZS(L)=Z                                                        001127
      TS(L)=R(1)                                                     001133
      THS(L)=R(2)/0.01745                                            001137
      PHIS(L)=R(3)/0.01745                                           001144
      VCS(L)=VC/1.689                                                001151
      THCS(L)=THEC/0.01745                                           001156
C                                                                    001156
C     RETURN TO MAIN PROGRAM IF END OF CABLE SEGMENT HAS BEEN REACHED 001156
C                                                                    001156
      IF(S.GE.SLL.AND.NUP.EQ.1) GO TO 90                             001163
      IF(S.LE.SLL.AND.NUP.EQ.2) GO TO 90                             001177
      L=L+1                                                          001214
      GO TO 49                                                       001217
   90 CONTINUE                                                       001221
      SF=STR                                                         001221
      SIF=S                                                          001222
      XF=X                                                           001224
```

```
00352        YF=Y                      001226
00353        ZF=Z                      001230
00354        TF=R(1)                   001232
00355        THF=R(2)                  001234
00356        PHIF=R(3)                 001236
00357        DM=DM*12.0                001240
00360        DD=DD*12.0                001243
00361        WC=WCCC                   001246
00362        RETURN                    001250
00363        END                       001466

     END OF COMPILATION:       NO DIAGNOSTICS.
```

```
@FOR,SI RUNGE,RUNGE
FOR 0E20-01/11/77-04:57:19 (,0)

   SUBROUTINE RUNGE      ENTRY POINT 000133

   STORAGE USED: CODE(1) 000162; DATA(0) 000104; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   NERR2$
    0004   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0001   000020 1L        0001   000120 10L       0001   000022 107G      0001   000053 120G      0001   000101 130G
    0001   000027 3L        0001   000031 4L        0001   000035 5L        0001   000073 7L        0001   000116 9L
    0000 R 000053 A         0000 I 000052 I         0000   000066 INJP$     0000 R 000000 Q


00101      1*          SUBROUTINE RUNGE(N,Y,D,X,H,M,K)                                           000002
00103      2*          DIMENSION Y(42),D(42),Q(42)                                               000002
00104      3*          M=M+1                                                                     000002
00105      4*          GO TO (1,4,5,3,7),M                                                       000005
00106      5*        1 DO 2 I=1,N                                                                000022
00111      6*        2 Q(I)=0.                                                                   000022
00113      7*          A=.5                                                                      000023
00114      8*          GO TO 9                                                                   000025
00115      9*        3 A=1.707107                                                                000027
00116     10*        4 X=X+.5*H                                                                  000031
00117     11*        5 DO 6 I=1,N                                                                000035
00122     12*          Y(I)=Y(I)+A*(D(I)*H-Q(I))                                                 000053
00123     13*        6 Q(I)=2.*A*H*D(I)+(1.-3.*A)*Q(I)                                           000060
00125     14*          A=.2928932                                                                000067
00126     15*          GO TO 9                                                                   000071
00127     16*        7 DO 8 I=1,N                                                                000101
00132     17*        8 Y(I)=Y(I)+H*D(I)/6.-Q(I)/3.                                               000101
00134     18*          M=0                                                                       000111
00135     19*          K=2                                                                       000112
00136     20*          GO TO 10                                                                  000114
00137     21*        9 K=1                                                                       000116
00140     22*       10 RETURN                                                                    000120
00141     23*          END                                                                       000161

      END OF COMPILATION:       NO  DIAGNOSTICS.
```

```
WFOR,SI ANGLE,ANGLE
FOR 0E26-01/11/77-04:57:21 (.0)

   SUBROUTINE ANGLE     ENTRY POINT 000063

   STORAGE USED: CODE(1) 000075; DATA(0) 000017; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0001   000023 115G      0001   000023 409L      0001   000034 410L      0001   000040 411L      0001   000044 412L
    0000 R 000000 A         0000   000011 INJP$     0000 I 000005 N         0000 R 000002 SEMI      0000 R 000004 SEMID
    0000 R 000003 SEMIM


00101      1*              SUBROUTINE ANGLE(THETA,PHI,NRAD)                                   000000
00101      2*        C                                                                         000000
00101      3*        C     THIS SUBROUTINE GETS THETA AND PHI TO BE BETWEEN -3.14 AND +3.14   000000
00101      4*        C        RADIANS IF NRAD=1 OR BETWEEN -180 AND +180 DEGREES IF NRAD=0    000000
00101      5*        C                                                                         000000
00103      6*              DIMENSION A(2)                                                     000000
00104      7*              A(1)=THETA                                                         000000
00105      8*              A(2)=PHI                                                           000001
00106      9*              IF(NRAD.EQ.1) SEMI=3.141592654                                     000003
00110     10*              IF(NRAD.EQ.0) SEMI=180.0                                           000010
00112     11*              SEMIM=-SEMI                                                        000014
00113     12*              SEMID=2.0*SEMI                                                     000016
00114     13*              DO 10 N=1,2                                                        000023
00117     14*          409 CONTINUE                                                           000023
00120     15*              IF(A(N).LT.SEMIM) GO TO 410                                        000023
00122     16*              IF(A(N).GT.SEMI) GO TO 411                                         000026
00124     17*              GO TO 412                                                          000032
00125     18*          410 CONTINUE                                                           000034
00126     19*              A(N)=A(N)+SEMID                                                    000034
00127     20*              GO TO 409                                                          000036
00130     21*          411 CONTINUE                                                           000040
00131     22*              A(N)=A(N)-SEMID                                                    000040
00132     23*              GO TO 409                                                          000042
00133     24*          412 CONTINUE                                                           000045
00134     25*           10 CONTINUE                                                           000045
00136     26*              THETA=A(1)                                                         000045
00137     27*              PHI=A(2)                                                           000047
00140     28*              RETURN                                                             000051
00141     29*              END                                                                000074

     END OF COMPILATION:        NO  DIAGNOSTICS.
```

```
@FOR,SI SUBSHF,SUBSHF
FOR 0E26-01/11/77-04157:22 (,0)

   SUBROUTINE SUBSHF    ENTRY POINT 000637

   STORAGE USED: CODE(1) 000736; DATA(0) 000120; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003    ANGLE
    0004    EXP
    0005    COS
    0006    SIN
    0007    ATAN
    0010    SQRT
    0011    NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0001     000056 19L       0001     000443 50L       0001     000502 55L       0001     000626 99L       0000 R 000023 AEX
    0000 R 000024 AEY       0000 R 000025 AEZ       0000 R 000020 B         0000 R 000014 C         0000 R 000013 CDS
    0000 R 000007 CDS1      0000 R 000010 CDS2      0000 R 000011 CDS3      0000 R 000012 CDS4      0000 R 000034 C1
    0000 R 000035 C2        0000 R 000036 C3        0000 R 000021 DFX       0000 R 000022 DFY       0000 R 000037 DS
    0000 I 000030 IERROR    0000   000065 INJP$     0000 R 000006 RE        0000 R 000031 TBDEX     0000 R 000032 TBDEY
    0000 R 000033 TBDEZ     0000 R 000015 TBEDX     0000 R 000016 TBEDY     0000 R 000017 TBEDZ     0000 R 000027 THBN
    0000 R 000026 THBP      0000 R 000005 VC        0000 R 000000 X         0000 R 000042 XDB       0000 R 000001 Y
    0000 R 000041 YDB       0000 R 000002 Z         0000 R 000003 ZAP       0000 R 000004 ZAPM      0000 R 000040 ZDB


00101            SUBROUTINE SUBSHF(IRROR,NUP,WS,RS,RHOW,TBED,THBED,PHBED,XED,YED,ZE            000000
00101           1D,G,H,RHC,TBDE,THBDE,PHBDE,XBDE,YBDE,ZBDE,LXX,DXX,THEC,CZZ,CB)                000000
00101        C                                                                                 000000
00101        C                                                                                 000000
00101        C   CALCULATE CURRENT MAGNITUDE AND DIRECTION                                     000000
00101        C                                                                                 000000
00103            X=XED                                                                         000000
00104            Y=YED                                                                         000003
00105            Z=ZED                                                                         000005
00106            ZAP=H-Z                                                                       000007
00107            IF(ZAP.GE.DXX) ZAP=DXX                                                        000013
00111            ZAPM=-ZAP*CZZ                                                                 000021
00112            ZAP=H-Z                                                                       000024
00113            IF(Z.GT.H) ZAPM=0.                                                            000026
00115            VC=(CXX*EXP(ZAPM))*1.689                                                      000033
00116            IF(ZAP.LE.DXX) GO TO 19                                                       000041
00120            VC=CB*1.689+(Z/(H-DXX))*(VC-CB*1.689)                                         000045
00121         19 CONTINUE                                                                      000056
00121        C                                                                                 000056
00121        C   SPECIFY COEFFICIENT OF DRAG FOR SPHERE                                        000056
00121        C   RE IS REYNOLDS NUMBER                                                         000056
00121        C                                                                                 000056
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```
00122        RE=VC*(2.*RS)/1.6E-5                                          000056
00123        COS1=0.5                                                      000062
00124        COS2=0.5*(EXP(-((RE-2.0E5)/4.9E4)))                           000064
00125        COS3=0.16*(EXP((RE-2.5E5)/1.4E6))                             000074
00126        COS4=0.2                                                      000105
00127        IF(RE.GE.3.0E4.AND.RE.LT.2.0E5) COS=COS1                      000107
00131        IF(RE.GE.2.0E5.AND.RE.LT.2.5E5) COS=COS2                      000127
00133        IF(RE.GE.2.5E5.AND.RE.LT.4.0E5) COS=COS3                      000166
00135        IF(RE.GE.4.0E5.AND.RE.LT.1.0E7) COS=COS4                      000206
00135  C                                                                   000206
00135  C     C=1 IF GOING TOWARD SHIP. =-1 IF GOING TOWARD ANCHOR           000206
00135  C                                                                   000206
00137        IF(NUP.EQ.1) C=1.                                             000226
00141        IF(NUP.EQ.2) C=-1.                                            000242
00141  C                                                                   000242
00141  C     CALCULATE TENSION COMPONENTS IN INERTIAL SYSTEM                000242
00141  C                                                                   000242
00143        TBEDX=-TBED*SIN(THBED)*COS(PHBED)                             000247
00144        TBEDY=TBED*COS(THBED)*COS(PHBED)                              000255
00145        TBEDZ=TBED*SIN(PHBED)                                         000263
00145  C                                                                   000263
00145  C     CALCULATE NET BUOYANCY                                        000263
00145  C                                                                   000263
00146        B=(64.4*(4./3.)*3.14159*RS**3)-WS                             000270
00146  C                                                                   000270
00146  C     CALCULATE DRAG COMPONENTS IN INERTIAL SYSTEM                  000270
00146  C                                                                   000270
00147        DFX=0.5*RHOW*COS*1.*3.14159*RS**2*(-VC)*SIN(THEC)*ABS((-VC)*SIN(TH  000275
00147       1EC))                                                          000275
00150        DFY=0.5*RHOW*COS*1.*3.14159*RS**2*VC*COS(THEC)*ABS(VC*COS(THEC))   000304
00150  C                                                                   000304
00150  C     CALCULATE CONSTANTS FOR SOLUTION TO UNKNOWN TENSION AND ANGLES 000304
00150  C                                                                   000304
00151        AEX=-TBEDX+(C*DFX)                                            000313
00152        AEY=TBEDY-(C*DFY)                                             000316
00153        AEZ=TBEDZ-(C*B)                                               000321
00154        THBP=90.*0.01745                                              000324
00155        THBN=-90.*0.01745                                             000326
00156        IF(AEY.EQ.0..AND.AEX.GE.0.) THBDE=THBP                        000327
00160        IF(AEY.EQ.0..AND.AEX.LE.0.) THBDE=THBN                        000343
00162        IF(AEY.EQ.0..AND.AEZ.GE.0.) PHBDE=THBP                        000357
00164        IF(AEY.EQ.0..AND.AEZ.LE.0.) PHBDE=THBN                        000373
00164  C                                                                   000373
00164  C     CALCULATE TENSION AND ANGLES AT UNKNOWN POINT                 000373
00164  C                                                                   000373
00166        IF(AEY.EQ.0..AND.AEX.GE.0.) GO TO 50                          000407
00170        IF(AEY.EQ.0..AND.AEX.LE.0.) GO TO 50                          000421
00172        THBDE=ATAN(AEX/AEY)                                           000433
00173     50 CONTINUE                                                      000443
00174        IF(AEY.EQ.0..AND.AEZ.LE.0.) GO TO 55                          000443
00176        IF(AEY.EQ.0..AND.AEZ.GE.0.) GO TO 55                          000454
00200        PHBDE=ATAN((AEZ/AEY)*COS(THBDE))                              000466
00201     55 CONTINUE                                                      000502
00202        IF(PHBDE.EQ.0.000) IERROR=1                                   000502
00204        IF(PHBDE.EQ.0.000) GO TO 99                                   000505
00206        TBDE=AEZ/SIN(PHBDE)                                           000507
00207        IF(TBDE.LE.0.) TBDE=0.                                        000515
```

```
00207      C                                                                 000515
00207      C      CALCULATE TENSION COMPONENTS AT UNKNOWN POINT IN INERTIAL SYSTEM 000515
00207      C                                                                 000515
00211             TBDEX=-TBDE*SIN(THBDE)*COS(PHBDE)                          000525
00212             TBDEY=TBDE*COS(THBDE)*COS(PHBDE)                           000533
00213             TBDEZ=TBDE*SIN(PHBDE)                                      000541
00213      C                                                                 000541
00213      C      CALCULATE COORDINATES OF UNKNOWN POINT                     000541
00213      C                                                                 000541
00214             C1=(B/2.)+TBDEZ                                            000546
00215             C2=(DFY/2.)+TBDEY                                          000552
00216             C3=(DFX/2.)+TBDEX                                          000556
00217             DS=2.*RS                                                   000562
00217      C                                                                 000562
00220             ZDB=DS/(SQRT((C2/C1)**2+(C3/C1)**2+1.))                    000565
00221             YDB=(C2/C1)*ZDB                                            000603
00222             XDB=(C3/C1)*ZDB                                            000605
00222      C                                                                 000605
00223             XBDE=XLD+XDB                                               000610
00224             YBDE=YED+YDB                                               000612
00225             ZBDE=ZED+ZDB                                               000614
00225      C                                                                 000614
00226             IERROR=0                                                   000617
00227             CALL ANGLE(THBDE,PHBDE,1)                                  000620
00230          99 CONTINUE                                                   000626
00231             RETURN                                                     000626
00232             END                                                        000735

     END OF COMPILATION:        NO DIAGNOSTICS.
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```
WFOR,SI TENCOR,TENCOR
FOR 0E28-01/11/77-04157124 (,0)

   SUBROUTINE TENCOR    ENTRY POINT 000226

   STORAGE USED: CODE(1) 000321; DATA(0) 000043; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   ANGLE
    0004   SQRT
    0005   COS
    0006   SIN
    0007   ATAN
    0010   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0001   000056 100L      0001   000211 110L      0001   000057 190L      0001   000102 230L      0001   000067 270L
    0001   000077 200L      0001   000102 300L      0001   000207 500L      0001   000043 70L       0001   000053 80L
    0000 R 000004 DELX      0000 R 000005 DELY      0000 R 000006 DELZ      0000 R 000000 ERRR      0000   000017 INJP$
    0000 R 000007 TTNX      0000 R 000010 TTNY      0000 R 000011 TTNZ      0000 R 000001 TTX       0000 R 000002 TTY
    0000 R 000003 TTZ


00101            SUBROUTINE TENCOR(EPS,Y,Z,ERRORP,DELTAP,TNSONT,THETAT,PHIT,XT,YT,Z      000000
00101           1T,TNSONN,THETAN,PHIN,ERRORN,DELTAN,LTEP,ITERTS)                          000000
00101       C                                                                            000000
00101       C    CALCULATE NEW CLOSURE ERROR                                             000000
00101       C                                                                            000000
00103            ERRORN=(0.-XT)**2+(Y-YT)**2+(Z-ZT)**2                                   000000
00104            ERRORN=SQRT(ERRORN)                                                     000012
00104       C                                                                            000012
00104       C    IS CLOSURE ERROR IN ACCEPTABLE RANGE                                    000012
00104       C                                                                            000012
00105            IF(ERRORN.LT.EPS) GO TO 500                                             000016
00106       C                                                                            000016
00107            DELTAN=DELTAP                                                           000021
00110            LTEP=0                                                                  000023
00110       C                                                                            000023
00110       C    DECREASE DELTA IF CLOSURE ERROR IS INCREASING                           000023
00110       C       OR IF OLD ERROR IS MORE THAN 2 TIMES NEW ERROR                       000023
00110       C                                                                            000023
00111            ERRR=ERRORP/ERRORN                                                      000024
00112            IF(ITERTS.GE.30) GO TO 190                                              000027
00114            IF(ERRORN.LE.500.0) GO TO 70                                            000033
00116            IF(ERRR.GT.2.0) GO TO 80                                                000037
00120         70 CONTINUE                                                                000043
00121            IF(ERRORN.LT.ERRORP) GO TO 100                                          000043
00123            DELTAN=DELTAN/2.                                                        000046
00124            GO TO 100                                                               000051
```

```
00125          80 CONTINUE                                                     000053
00126             DELTAN=DELTAN/2.                                             000053
00127         100 CONTINUE                                                     000056
00130             GO TO 230                                                    000056
00131         190 CONTINUE                                                     000057
00132             IF(ERRORN.LE.500.) GO TO 270                                 000057
00134             IF(ERRR.GT.2.0) GO TO 280                                    000062
00136         270 CONTINUE                                                     000067
00137             IF(ERRORN.LT.ERRORP) GO TO 300                               000067
00141             DELTAN=DELTAN/1.2                                            000072
00142             GO TO 300                                                    000075
00143         280 CONTINUE                                                     000077
00144             DELTAN=DELTAN/1.2                                            000077
00145         300 CONTINUE                                                     000102
00146         230 CONTINUE                                                     000102
00146       C                                                                  000102
00146       C     CALCULATE TENSION COMPONENTS IN INERTIAL SYSTEM              000102
00146       C                                                                  000102
00147             TTX=-TNSONT*SIN(THETAT)*COS(PHIT)                            000102
00150             TTY=TNSONT*COS(THETAT)*COS(PHIT)                             000113
00151             TTZ=TNSONT*SIN(PHIT)                                         000121
00151       C                                                                  000121
00151       C     CALCULATE TENSION CORRECTIONS                                000121
00151       C                                                                  000121
00152             DELX=(DELTAN/ERRORN)*(XT)*(-1.)                              000126
00153             DELY=(DELTAN/ERRORN)*(YT-Y)*(-1.)                            000133
00154             DELZ=(DELTAN/ERRORN)*(ZT-Z)*(-1.)                            000137
00154       C                                                                  000137
00154       C     CALCULATE CORRECTED TENSION COMPONENTS                       000137
00154       C                                                                  000137
00155             TTNX=TTX+DELX                                                000143
00156             TTNY=TTY+DELY                                                000145
00157             TTNZ=TTZ+DELZ                                                000147
00157       C                                                                  000147
00157       C     CONVERT TENSION COMPONENTS INTO TENSION MAGNITUDE AND ANGLES  000147
00157       C                                                                  000147
00160             TNSONN=SQRT(TTNX**2+TTNY**2+TTNZ**2)                         000151
00161             PHIN=ATAN(TTNZ/(SQRT(TTNX**2+TTNY**2)))                      000164
00162             THETAN=ATAN(-(TTNX)/TTNY)                                    000176
00163             GO TO 110                                                    000205
00164         500 CONTINUE                                                     000207
00165             LTEP=1                                                       000207
00166         110 CONTINUE                                                     000211
00167             CALL ANGLE(THETAN,PHIN,1)                                    000211
00170             RETURN                                                       000215
00171             END                                                          000320

    END OF COMPILATION:        NO DIAGNOSTICS.
```

```
@FOR,SI DYMICS.DYMICS
FOR 0E2B-01/11/77-04:57:25 (,0)

   SUBROUTINE DYMICS    ENTRY POINT 003726

   STORAGE USED: CODE(1) 004111; DATA(0) 022143; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   RUNGE
    0004   MODESG
    0005   SETSMG
    0006   SUBVEG
    0007   GRAPHG
    0010   POINTG
    0011   LINESG
    0012   PAGEG
    0013   EXITG
    0014   SIN
    0015   COS
    0016   ATAN
    0017   SQRT
    0020   EXP
    0021   NERR2$
    0022   NPRT$
    0023   NIO2$
    0024   NIO1$
    0025   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0001     003061 1037G    0001     003141 1053G    0001     003221 1067G    0001     003310 1105G    0001     003376 1132G
    0001     003466 1150G    0001     003544 1163G    0001     003622 1176G    0001     002337 118L     0001     000072 1206
    0001     002316 120L     0001     002503 125L     0001     000120 132G     0001     002520 134L     0000     021652 135F
    0000     021657 136F     0001     002550 140L     0001     002554 141L     0001     002560 142L     0000     021666 143F
    0001     002564 144L     0000     021676 145F     0001     000164 145G     0001     002570 146L     0000     021672 147F
    0000     021726 150F     0000     021753 160F     0001     000211 161G     0001     000134 20L      0001     000342 203G
    0000     021760 211F     0001     000512 225G     0001     003273 245L     0001     000603 251G     0001     003672 285L
    0001     003677 301L     0001     001002 302G     0000     021625 34F      0001     001414 350G     0001     001433 357G
    0001     001722 415G     0001     001756 427G     0000     021644 499F     0001     002226 505G     0001     002407 510L
    0000     021646 512F     0001     002320 532G     0001     002353 557G     0001     000571 58L      0001     002441 613G
    0001     002531 646G     0001     002611 713G     0001     002677 755G     0001     002735 777G     0001     001713 79L
    0001     002206 99L      0000 R  000334 ACC      0000 R  021513 ACX      0000 R  021514 ACZ      0000 R  021500 B
    0000 R  021543 CDN      0000 R  021540 CDN1     0000 R  021541 CDN2     0000 R  021542 CDN3     0000 R  021570 CDS
    0000 R  021564 CDS1     0000 R  021565 CDS2     0000 R  021566 CDS3     0000 R  021567 CDS4     0000 R  021545 CDT
    0000 R  021544 CDT1     0000 R  021532 CPH      0000 R  021536 CPI      0000 R  021534 CTE      0000 R  021530 CTH
    0000 R  021164 C1       0000 R  021330 C2       0000 R  000262 D        0000 R  021572 DPA      0000 R  021573 DPX
    0000 R  021574 DBY      0000 R  021575 DBZ      0000 R  010504 DISP     0000 R  021507 DISX     0000 R  021510 DISZ
    0000 R  000202 DRGX     0000 R  021546 DRGX1    0000 R  021551 DRGX2    0000 R  000210 DRGY     0000 R  021547 DRGY1
    0000 R  021552 DRGY2    0000 R  000216 DRGZ     0000 R  021550 DRGZ1    0000 R  021553 DRGZ2    0000 R  021554 EMU
    0000 R  021576 EMUB     0000 R  021555 ENV      0000 R  000232 ERTIAX   0000 R  000240 ERTIAY   0000 R  000246 ERTIAZ
    0000 R  021577 HYDB     0000 R  021556 HYDRMX   0000 R  021557 HYDRMY   0000 R  021560 HYDRMZ   0000 R  021561 HYDRNX
    0000 R  021562 HYDRNY   0000 R  021563 HYDRNZ   0000 I  000254 IB       0000 I  021602 IMAX     0000     022035 INJP$
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0000 I 021601 IIM      0000 I 021605 IIMAX    0000 I 021603 J      0000 I 021476 K      0000 I 021506 L
0000 I 021502 LAST     0000 I 021477 M        0000 I 021505 N      0000 I 021604 NTME   0000 R 020654 P
0000 R 000061 PHI      0000 R 000000 R        0000 R 021537 RE     0000 R 021531 SPH    0000 R 021535 SPI
0000 R 021520 SPRCHT   0000 R 021533 STE      0000 R 021527 STH    0000 R 000070 T      0000 R 000052 THETA
0000 R 021503 TLAST    0000 R 021475 TM       0000 R 021501 TMCNT  0000 R 021504 TMCT   0000 R 021624 TMMIN
0000 R 021474 TMSTOR   0000 R 021623 TMMAX    0000 R 021617 TNMIN  0000 R 014570 TMS    0000 R 000106 TX
0000 R 000114 TY       0000 R 000122 TZ       0000 R 021523 U      0000 R 000130 UR     0000 R 021525 UXN
0000 R 021524 V        0000 R 000077 VC       0000 R 004420 VEL    0000 R 021600 VIRM   0000 R 021511 VLX
0000 R 021512 VLZ      0000 R 000146 VR       0000 R 021620 VXMAX  0000 R 021614 VXMIN  0000 R 021621 VYMAX
0000 R 021615 VYMIN    0000 R 021526 VYN      0000 R 021622 VZMAX  0000 R 021616 VZMIN  0000 R 000164 WR
0000 R 000224 WTHM     0000 R 021571 WZN      0000 R 021611 XMAX   0000 R 021606 XMIN   0000 R 021515 XND
0000 R 021612 YMAX     0000 R 021607 YMIN     0000 R 021516 YND    0000 R 021521 ZAP    0000 R 021522 ZAPM
0000 R 021613 ZMAX     0000 R 021610 ZMIN     0000 R 021517 ZND

00101          SUBROUTINE DYMICS(X1,Y1,Z1,DS,EC,DL,G,H,CAX,CZZ,CB,                     000043
00101         1DXX,THEC,DCUT,RHOW,WC,IBUOY,RAD,EXB,WT,TMMAX,XCHAR,YCHAR,               000043
00101         2ZCHAR,XCHRR,YCHRR,ZCHRR,VELX,VELY,VELZ,TFN,TIN,TITLE,IPLOT,SHX,         000043
00101         3SHZ,OMEGAX,OMEGAZ,PHAX,PHAZ)                                            000043
00103          DIMENSION X1(7),Y1(7),Z1(7),R(42),THETA(7),PHI(7),DS(6),EC(6),DL(6      000043
00103         1),T(7),VC(7),TX(6),TY(6),TZ(6),UR(7,2),VR(7,2),WR(7,2),DOUT(6),         000043
00103         2DRGX(6),DRGY(6),DRGZ(6),WC(6),WTRM(6),ERTIAX(6),ERTIAY(6),ERTIAZ(6      000043
00103         3),IB(6),RAD(6),EXB(6),WT(6),D(42),ACC(7,3,100),VEL(7,3,100),DISP(7      000043
00103         4,3,100),TMS(7,3,100)                                                    000043
00104          DIMENSION P(200),C1(100),C2(100)                                        000043
00105          DIMENSION SHX(101),SHZ(101),OMEGAX(101),OMEGAZ(101),PHAX(101),          000043
00105         1PHAZ(101)                                                               000043
00105    C                                                                             000043
00105    C     INITIAL VALUES AT TIME=0                                                000043
00105    C                                                                             000043
00106          TMSTOR=TMMAX                                                            000043
00107          TM=0.                                                                   000045
00110          K=0                                                                     000046
00111          M=0                                                                     000047
00112          B=0.1                                                                   000050
00113          TMCNT=10.                                                               000052
00114          LAST=50                                                                 000054
00115          TLAST=LAST                                                              000056
00116          TMCT=TMMAX-TLAST                                                        000061
00117          DO 10 N=1,7                                                             000072
00122          L=N*6                                                                   000072
00123          R(L-5)=0.                                                               000076
00124          R(L-4)=X1(N)                                                            000077
00125          R(L-3)=0.                                                               000101
00126          R(L-2)=Y1(N)                                                            000102
00127          R(L-1)=0.                                                               000104
00130          R(L)=Z1(N)                                                              000105
00131          DO 5 K=1,7                                                              000120
00134          DISP(K,1,1)=X1(K)                                                       000120
00135          DISP(K,2,1)=Y1(K)                                                       000121
00136          DISP(K,3,1)=Z1(K)                                                       000123
00137        5 CONTINUE                                                                000134
00141       10 CONTINUE                                                                000134
00143       20 CONTINUE                                                                000134
00143    C                                                                             000134
```

AD-A039 831 NAVAL UNDERWATER SYSTEMS CENTER NEW LONDON CONN NEW --ETC F/G 13/10
A STEADY STATE AND DYNAMIC ANALYSIS OF A MOORING SYSTEM.(U)
MAR 77 J P RADOCHIA
UNCLASSIFIED NUSC-TR-5597 NL

3 OF 3
ADA039 831

END
DATE
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6-77

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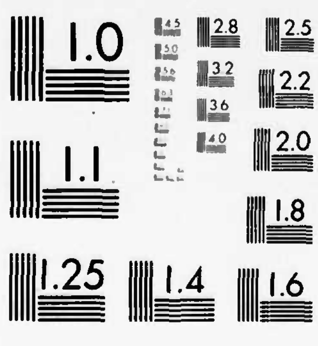

MICROCOPY RESOLUTION TEST CHART

NATIONAL BUREAU OF STANDARDS-1963-A

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00143      C     BOUNDARY CONDITIONS                                      000134
00143      C                                                              000134
00144            DO 30 N=1,6                                              000134
00147            R(N)=0.                                                  000164
00150         30 CONTINUE                                                 000165
00150      C                                                              000165
00150      C     SHIP MOTIONS                                             000165
00150      C                                                              000165
00152            DISX=0.                                                  000165
00153            DISZ=0.                                                  000166
00154            VLX=0.                                                   000167
00155            VLZ=0.                                                   000170
00156            ACX=0.                                                   000171
00157            ACZ=0.                                                   000172
00160            DO 35 N=1,101                                            000211
00163            DISX=DISX+(SHX(N)*SIN(OMEGAX(N)*TM+PHAX(N)))             000211
00164            DISZ=DISZ+(SHZ(N)*SIN(OMEGAZ(N)*TM+PHAZ(N)))             000222
00165            VLX=VLX+(SHX(N)*OMEGAX(N)*COS(OMEGAX(N)*TM+PHAX(N)))     000234
00166            VLZ=VLZ+(SHZ(N)*OMEGAZ(N)*COS(OMEGAZ(N)*TM+PHAZ(N)))     000250
00167            ACX=ACX-(SHX(N)*OMEGAX(N)**2*SIN(OMEGAX(N)*TM+PHAX(N)))  000264
00170            ACZ=ACZ-(SHZ(N)*OMEGAZ(N)**2*SIN(OMEGAZ(N)*TM+PHAZ(N)))  000301
00171         35 CONTINUE                                                 000317
00173            DISZ=DISZ+H                                              000317
00174            R(37)=VLX                                                000322
00175            R(38)=DISX                                               000324
00176            R(39)=0.                                                 000326
00177            R(40)=0                                                  000327
00200            R(41)=VLZ                                                000331
00201            R(42)=DISZ                                               000333
00201      C                                                              000333
00201      C     CABLE ANGLES,TENSIONS,AND TENSION COMPONENTS             000333
00201      C                                                              000333
00202            DO 40 N=1,6                                              000342
00205            L=N*6                                                    000342
00206            XND=R(L+2)-R(L-4)                                        000346
00207            YND=R(L+4)-R(L-2)                                        000351
00210            ZND=R(L+6)-R(L)                                          000354
00211            THETA(N)=ATAN(-(XND)/YND)                                000357
00212            PHI(N)=ATAN(ZND/(SQRT(XND**2+YND**2)))                   000365
00213            SPRCNT=(3.14159*DS(N)**2*EC(N))/(4.*DL(N))               000404
00214            T(N)=SPRCNT*(SQRT(XND**2+YND**2+ZND**2)-DL(N))           000414
00216            IF(T(N).LE.0.) T(N)=0.                                   000433
00217            TX(N)=-T(N)*SIN(THETA(N))*COS(PHI(N))                    000437
00220            TY(N)=T(N)*COS(THETA(N))*COS(PHI(N))                     000455
00221            TZ(N)=T(N)*SIN(PHI(N))                                   000473
00222         40 CONTINUE                                                 000512
00222      C                                                              000512
00222      C     CURRENT VELOCITY IN INERTIAL COORDINATES                 000512
00222      C                                                              000512
00224            DO 50 N=1,7                                              000512
00227            L=N*6                                                    000512
00230            ZAP=H-R(L)                                               000516
00231            IF(ZAP.GE.DXX) ZAP=DXX                                   000522
00233            ZAPM=-ZAP*CZZ                                            000530
00234            ZAP=H-R(L)                                               000533
00235            IF(R(L).GT.H) ZAPM=0.                                    000537
00237            VC(N)=(CXA*EXP(ZAPM))*1.689                              000545
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00240            IF(ZAP.LE.DXX) GO TO 58                                        000553
00242            VC(N)=CB*1.689+(R(L)/(H-DXX))*(VC(N)-CD*1.689(                 000557
00243         58 CONTINUE                                                        000571
00244            U=-VC(N)*SIN(THEC)                                              000571
00245            V=VC(N)*COS(THEC)                                               000573
00246         50 CONTINUE                                                        000603
00246      C                                                                     000603
00246      C     CURRENT COMPONENTS IN INERTIAL COORDINATES                      000603
00246      C                                                                     000603
00250            DO 59 N=2,7                                                     000603
00253            L=N*6                                                           000603
00254            UR(1)=0.                                                        000607
00255            VR(1)=0.                                                        000610
00256            WR(1)=0.                                                        000611
00257            UXN=U-R(L-5)                                                    000612
00260            VYN=V-R(L-3)                                                    000615
00261            STH=SIN(THETA(N-1))                                             000620
00262            CTH=COS(THETA(N-1))                                             000626
00263            SPH=SIN(PHI(N-1))                                               000634
00264            CPH=COS(PHI(N-1))                                               000642
00265            STE=SIN(THETA(N))                                               000650
00266            CTE=COS(THETA(N))                                               000656
00267            SPI=SIN(PHI(N))                                                 000664
00270            CPI=COS(PHI(N))                                                 000672
00270      C                                                                     000672
00270      C     CURRENT COMPONENTS IN CABLE COORDINATES                         000672
00270      C                                                                     000672
00271            UR(N,1)=UXN*CTH+VYN*STH                                         000700
00272            VR(N,1)=-UXN*STH*CPH+VYN*CTH*CPH-R(L-1)*SPH                     000706
00273            WR(N,1)=UXN*STH*SPH-VYN*CTH*SPH-R(L-1)*CPH                      000721
00274            UR(N,2)=UXN*CTE+VYN*STE                                         000734
00275            VR(N,2)=-UXN*STE*CPI+VYN*CTE*CP)-R(L-1)*SP)                     000742
00276            WR(N,2)=UXN*STE*SPI-VYN*CTE*SPI-R(L-1)*CPI                      000755
00277         59 CONTINUE                                                        000772
00301            DO 60 N=2,6                                                     000772
00301      C                                                                     000772
00301      C     CABLE DRAG COEFFICIENTS FOR REYNOLDS NUMBER RE                  000772
00301      C                                                                     000772
00304            RE=VC(N)*DOUT(N-1)/1.6E-5                                       001002
00305            CDN1=1.2*(EXP(-((RE-2.0E2)/8.0E3)))                             001005
00306            CDN2=0.9*(EXP((RE-2.5E3)/4.3E4))                                001015
00307            CDN3=1.2                                                        001026
00310            IF(RE.GE.2.0E2.AND.RE.LT.2.5E3) CDN=CDN1                        001030
00312            IF(RE.GE.2.5E3.AND.RE.LT.1.5E4) CDN=CDN2                        001050
00314            IF(RE.GE.1.5E4.AND.RE.LT.2.0E5) CDN=CDN3                        001070
00316            CDT1=0.006*(EXP(-((RE-2.0E3)/2.2E5)))                           001110
00317            IF(RE.GE.2.0E3.AND.RE.LE.2.0E5) CDT=CDT1                        001121
00317      C                                                                     001121
00317      C     DRAG COMPONENTS IN CABLE COORDINATES                            001121
00317      C                                                                     001121
00321            DRGX(1)=0.                                                      001141
00322            DRGY(1)=0.                                                      001142
00323            DRGZ(1)=0.                                                      001143
00324            DRGX1=0.5*RHOW*DOUT(N-1)*CDN*UR(N,1)*ABS(UR(N,1))               001144
00325            DRGY1=0.5*RHOW*3.14159*DOUT(N-1)*CDT*VR(N,1)*ABS(VR(N,1))       001153
00326            DRGZ1=0.5*RHOW*DOUT(N-1)*CDN*WR(N,1)*ABS(WR(N,1))               001162
00327            DRGX2=0.5*RHOW*DOUT(N)*CDN*UR(N,2)*ABS(UR(N,2))                 001171
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00330       DRGY2=0.5*RHOW*3.14159*DOUT(N)*CDI*VR(N,2)*ABS(VR(N,2))                     001200
00331       DRGZ2=0.5*RHOW*DOUT(N)*CDN*WR(N,2)*ABS(WR(N,2))                             001207
00332       STH=SIN(THETA(N))                                                           001216
00333       CTH=COS(THETA(N))                                                           001224
00334       SPH=SIN(PHI(N))                                                             001232
00335       CPH=COS(PHI(N))                                                             001240
00336       STE=SIN(THETA(N-1))                                                         001246
00337       CTE=COS(THETA(N-1))                                                         001254
00340       SP1=SIN(PHI(N-1))                                                           001262
00341       CP1=COS(PHI(N-1))                                                           001270
00341 C                                                                                 001270
00341 C     DRAG COMPONENTS IN INERTIAL COORDINATES                                     001270
00341 C                                                                                 001270
00342       DRGX(N)=(DRGX1*CTE-DRGY1*STE*CP1+DRGZ1*STE*SP1)*(DL(N-1)/2.)+               001276
00342      1(DRGX2*CTH-DRGY2*STH*CPH+DRGZ2*STH*SPH)*(DL(N)/2.)                          001276
00343       DRGT(N)=(DRGX1*STE+DRGY1*CTE*CP1-DRGZ1*CTE*SP1)*(DL(N-1)/2.)+               001326
00343      1(DRGX2*STH+DRGT2*CTH*CPH-DRGZ2*CTH*SPH)*(DL(N)/2.)                          001326
00344       DRGZ(N)=(DRGT1*SP1+DRGZ1*CP1)*(DL(N-1)/2.)+(DRGY2*SPH+DRGZ2*CPH)*           001362
00344      1(DL(N)/2.)                                                                  001362
00345    60 CONTINUE                                                                    001414
00345 C                                                                                 001414
00345 C     CABLE WEIGHT IN INERTIAL COORDINATES                                        001414
00345 C                                                                                 001414
00347       DO 70 N=2,6                                                                 001414
00352       WTRM(1)=0.                                                                  001414
00353       WTRM(N)=(WC(N-1)*(DL(N-1)/2.))+(WC(N)*(DL(N)/2.))                           001414
00354    70 CONTINUE                                                                    001433
00354 C                                                                                 001433
00354 C     STRUCTURAL MASS                                                             001433
00354 C                                                                                 001433
00356       DO 80 N=2,6                                                                 001433
00361       EMU=(((3.14159*(DOUT(N)/2.)**2*64.4)+WC(N))/32.2)*(DL(N)/2.)                001441
00362       EMV=(((3.14159*(DOUT(N-1)/2.)**2*64.4)+WC(N-1))/32.2)*(DL(N-1)/2.)          001453
00362 C                                                                                 001453
00362 C     HYDRODYNAMIC MASS                                                           001453
00362 C                                                                                 001453
00363       HYDRMX=(3.14159*RHOW*(DOUT(N)/2.)**2)*(DL(N)/2.)                            001465
00364       HYDRMY=0.                                                                   001474
00365       HYDRMZ=HYDRMX                                                               001475
00366       HYDRNX=(3.14159*RHOW*(DOUT(N-1)/2.)**2)*(DL(N-1)/2.)                        001476
00367       HYDRNY=0.                                                                   001505
00370       HYDRNZ=HYDRNX                                                               001506
00370 C                                                                                 001506
00370 C     INERTIAL TERMS                                                              001506
00370 C                                                                                 001506
00371       ERTIAX(1)=0.                                                                001507
00372       ERTIAY(1)=0.                                                                001510
00373       ERTIAZ(1)=0.                                                                001511
00374       IF(N.EQ.1) GO TO 79                                                         001512
00376       STH=SIN(THETA(N))                                                           001515
00377       CTH=COS(THETA(N))                                                           001523
00400       SPH=SIN(PHI(N))                                                             001531
00401       CPH=COS(PHI(N))                                                             001537
00402       STE=SIN(THETA(N-1))                                                         001545
00403       CTE=COS(THETA(N-1))                                                         001553
00404       SP1=SIN(PHI(N-1))                                                           001561
00405       CP1=COS(PHI(N-1))                                                           001567
```

```
00406        ERTIAX(N)=EMV+ABS(HYDRNX*CTE)+ABS(HYDRNY*STE*CPI)+ABS(HYDRNZ*STE*S   001575
00406       1PI)+EMU+ABS(HYDRMX*CTH)+ABS(HYDRMY*STH*CPH)+ABS(HYDRMZ*STH*SPH)     001575
00407        ERTIAY(N)=EMV+ABS(HYDRNX*STE)+ABS(HYDRNY*CTE*CPI)+ABS(HYDRNZ*CTE*S   001632
00407       1PI)+EMU+ABS(HYDRMX*STH)+ABS(HYDRMY*CTH*CPH)+ABS(HYDRMZ*CTH*SPH)     001632
00410        ERTIAZ(N)=EMV+ABS(HYDRNY*SPI)+ABS(HYDRNZ*CPI)+EMU+ABS(HYDRMY*SPH)+   001670
00410       1ABS(HYDRMZ*CPH)                                                    001670
00411     79 CONTINUE                                                           001722
00412     80 CONTINUE                                                           001722
00412  C                                                                        001722
00412  C     CHECK FOR BUOYS                                                    001722
00412  C                                                                        001722
00414        DO 90 N=1,6                                                        001722
00417        IB(N)=0                                                            001722
00420     90 CONTINUE                                                           001724
00422        IF(IBUOY.EQ.1.OR.IBUOY.EQ.2) IB(4)=1                               001724
00424        IF(IBUOY.EQ.2) IB(5)=1                                             001742
00426        DO 100 N=2,6                                                       001756
00431        IF(IB(N).EQ.0) GO TO 99                                            001756
00431  C                                                                        001756
00431  C     COEFFICIENT OF DRAG FOR SPHERE AT REYNOLDS NUMBER RE                001756
00431  C                                                                        001756
00433        RE=VC(N)*(2.*RAD(N))/1.6E-5                                        001757
00434        CDS1=0.5                                                           001764
00435        CDS2=0.5*(EXP(-((RE-2.0E5)/4.9E4)))                                001766
00436        CDS3=0.18*(EXP((RE-2.5E5)/1.4E6))                                  001776
00437        CDS4=0.2                                                           002007
00440        IF(RE.GE.3.0E4.AND.RE.LT.2.0E5) CDS=CDS1                           002011
00442        IF(RE.GE.2.0E5.AND.RE.LT.2.5E5) CDS=CDS2                           002031
00444        IF(RE.GE.2.5E5.AND.RE.LT.4.0E5) CDS=CDS3                           002051
00446        IF(RE.GE.4.0E5.AND.RE.LT.1.0E7) CDS=CDS4                           002071
00446  C                                                                        002071
00446  C     DRAG TERMS FOR SPHERE                                              002071
00446  C                                                                        002071
00450        U=-VC(N)*SIN(THEC)                                                 002111
00451        V=VC(N)*COS(THEC)                                                  002114
00452        UXN=U-R(L-5)                                                       002117
00453        VYN=V-R(L-3)                                                       002121
00454        WZN=-R(L-1)                                                        002123
00455        DBA=0.5*RHOW*CDS*3.14159*(RAD(N))**2                               002125
00456        DBX=DBA*UXN*ABS(UXN)                                               002134
00457        DBY=DBA*VYN*ABS(VYN)                                               002140
00460        DBZ=DBA*WZN*ABS(WZN)                                               002145
00461        DRGX(N)=DRGX(N)+DBX                                                002152
00462        DRGY(N)=DRGY(N)+DBY                                                002154
00463        DRGZ(N)=DRGZ(N)+DBZ                                                002156
00463  C                                                                        002156
00463  C     BUOY WEIGHT IN WATER                                               002156
00463  C                                                                        002156
00464        WTHM(N)=WTRM(N)-EXB(N)                                             002160
00464  C                                                                        002160
00464  C     STRUCTURAL MASS OF BUOY                                            002160
00464  C                                                                        002160
00465        EMUB=WT(N)/32.2                                                    002163
00465  C                                                                        002163
00465  C     HYDRODYNAMIC MASS OF BUOY                                          002163
00465  C                                                                        002163
00466        HYDB=(2./3.)*3.14159*RHOW*RAD(N)**3                                002166
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00466   C                                                        002166
00466   C     VIRTUAL MASS OF BUOY                               002166
00466   C                                                        002166
00467         VIRM=HYDB+EMUB                                     002173
00470         ERTIAX(N)=ERTIAX(N)+VIRM                           002175
00471         ERTIAY(N)=ERTIAY(N)+VIRM                           002177
00472         ERTIAZ(N)=ERTIAZ(N)+VIRM                           002202
00473      99 CONTINUE                                           002212
00474     100 CONTINUE                                           002212
00474   C                                                        002212
00474   C     DYNAMIC CABLE EQUATIONS                            002212
00474   C                                                        002212
00474   C     ANCHOR                                             002212
00476         D(1)=0.                                            002212
00477         D(2)=R(1)                                          002213
00500         D(3)=0.                                            002215
00501         D(4)=R(3)                                          002216
00502         D(5)=0.                                            002220
00503         D(6)=R(5)                                          002221
00503   C     CABLE ELEMENTS                                     002221
00504         DO 110 N=2,6                                       002226
00507         L=N*6                                              002226
00510         D(L-5)=(DRGX(N)+TX(N)-TX(N-1))/ERTIAX(N)           002232
00511         D(L-4)=R(L-5)                                      002237
00512         D(L-3)=(DRGY(N)+TY(N)-TY(N-1))/ERTIAY(N)           002241
00513         D(L-2)=R(L-3)                                      002246
00514         D(L-1)=(-WIRM(N)+DRGZ(N)+TZ(N)-TZ(N-1))/ERTIAZ(N)  002250
00515         D(L)=R(L-1)                                        002256
00516     110 CONTINUE                                           002262
00516   C     SHIP                                               002262
00520         D(37)=ACX                                          002262
00521         D(38)=R(37)                                        002264
00522         D(39)=0.                                           002266
00523         D(40)=R(39)                                        002267
00524         D(41)=ACZ                                          002271
00525         D(42)=R(41)                                        002273
00525   C                                                        002273
00525   C     INTEGRATE EQUATIONS                                002273
00525   C                                                        002273
00526         CALL RUNGE(42,R,D,TM,B,M,K)                        002275
00527         GO TO(20,120),K                                    002306
00530     120 CONTINUE                                           002320
00530   C                                                        002320
00530   C     CHECK IF MAXIMUM TENSION HAS BEEN EXCEEDED         002320
00530   C                                                        002320
00531         DO 119 N=1,6                                       002320
00534         IF(T(N).LE.60000.) GO TO 118                       002320
00536         PRINT 34,T(N),N,TM                                 002324
00543      34 FORMAT(1H1,'CABLE BREAKS AT',F20.5,' LBS AT SEGMENT NUMBER',I5,' A  002333
00543        1T',F10.3,' SECONDS')                               002333
00544         TMMAX=TM                                           002333
00545         GO TO 134                                          002335
00546     118 CONTINUE                                           002340
00547     119 CONTINUE                                           002340
00547   C                                                        002340
00547   C     STORE VALUES EVERY SECOND                          002340
00547   C                                                        002340
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00547   C                                                                  002340
00547   C                                                                  002340
00551         IF(TM.LT.TMCHI) GO TO 510                                    002340
00553         PRINT 499                                                    002344
00555   499   FORMAT('      ')                                             002353
00556         DO 511 N=1,7                                                 002353
00561         L=N*6                                                        002353
00562         PRINT 512,TM,D(L-5),D(L-3),D(L-1),D(L-4),D(L-2),D(L),R(L-4),R(L-2)   002356
00562        1,R(L),T(N),THETA(N),PHI(N)                                   002356
00601   511   CONTINUE                                                     002403
00603         TMCHI=TMCHI+10.                                              002403
00604   512   FORMAT(7F10.4,4F10.1,2F10.2)                                 002407
00605   510   CONTINUE                                                     002407
00605   C                                                                  002407
00605   C                                                                  002407
00606         IF(TM.LT.TMCT) GO TO 20                                      002407
00610         TMCT=TMCT+1.                                                 002412
00611         ITM=TMCT-(TMMAX-TLAST)                                       002415
00612         DO 130 N=1,7                                                 002427
00615         L=N*6                                                        002441
00616         ACC(N,1,ITM)=D(L-5)                                          002444
00617         ACC(N,2,ITM)=D(L-3)                                          002447
00620         ACC(N,3,ITM)=D(L-1)                                          002451
00621         VEL(N,1,ITM)=D(L-4)                                          002453
00622         VEL(N,2,ITM)=D(L-2)                                          002455
00623         VEL(N,3,ITM)=D(L)                                            002457
00624         DISP(N,1,ITM)=R(L-4)                                         002461
00625         DISP(N,2,ITM)=R(L-2)                                         002463
00626         DISP(N,3,ITM)=R(L)                                           002465
00627         IF(N.EQ.7) GO TO 125                                         002467
00631         TNS(N,1,ITM)=T(N)                                            002472
00632         TNS(N,2,ITM)=THETA(N)*57.3                                   002474
00633         TNS(N,3,ITM)=PHI(N)*57.3                                     002477
00634   125   CONTINUE                                                     002503
00635         TNS(7,1,ITM)=TNS(6,1,ITM)                                    002503
00636         TNS(7,2,ITM)=TNS(6,2,ITM)                                    002504
00637         TNS(7,3,ITM)=TNS(6,3,ITM)                                    002506
00640   130   CONTINUE                                                     002513
00642         IF(TM.LT.TMMAX) GO TO 20                                     002513
00642   C                                                                  002513
00642   C     PRINTED OUTPUT                                               002513
00642   C                                                                  002513
00644   134   CONTINUE                                                     002520
00645         DO 210 N=1,7                                                 002520
00650         L=N*6                                                        002531
00651         PRINT 135,N                                                  002534
00654   135   FORMAT(1H1,'ELEMENT NUMBER',I2)                              002541
00655         IF(IB(N).EQ.0) GO TO 140                                     002541
00657         PRINT 136                                                    002543
00661   136   FORMAT(1H ,18X,'(INCLUDES SUBSURFACE BUOY)')                 002550
00662   140   CONTINUE                                                     002550
00663         IF(N.EQ.1) GO TO 141                                         002550
00665         GO TO 142                                                    002552
00666   141   CONTINUE                                                     002554
00667         PRINT 143                                                    002554
00671   143   FORMAT(1H ,18X,'(ANCHOR)')                                   002560
00672   142   CONTINUE                                                     002560
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00673        IF(N.LQ.7) GO TO 144                                                  002561
00675        GO TO 146                                                             002562
00676    144 CONTINUE                                                              002564
00677        PRINT 147                                                             002564
00701    147 FORMAT(1H+,13X,'(SHIP)')                                              002570
00702    146 CONTINUE                                                              002570
00703        PRINT 145                                                             002570
00705    145 FORMAT(//1H ,' TIME(SEC)',3X,'ACCELERATION (FT/SEC**2)',10X,          002573
00705       1'VELOCITY (FT/SEC)',13X,'DISPLACEMENT (FT)',6X,'TENSN(LBS)',5X,       002573
00705       2'ANGLES(DEG)')                                                        002573
00706        PRINT 150                                                             002573
00710    150 FORMAT(/1H ,15X,'X',9X,'Y',9X,'Z',9X,'X',9X,'Y',9X,'Z',9X,'X',9X,'    002577
00710       1Y',9X,'Z',9X,'T',6X,'THETA',7X,'PHI')                                 002577
00711        IMAX=LAST+1                                                           002577
00712        DO 200 J=1,IMAX                                                       002603
00715        NTME=(TMMAX-(TLAST+1.))+J                                             002611
00716    155 CONTINUE                                                              002624
00717        PRINT 160,NTME,ACC(N,1,J),ACC(N,2,J),ACC(N,3,J),VEL(N,1,J),VEL(N,2    002624
00717       1,J),VEL(N,3,J),DISP(N,1,J),DISP(N,2,J),DISP(N,3,J),TNS(N,1,J),TNS(    002624
00717       2N,2,J),TNS(N,3,J)                                                     002624
00736    160 FORMAT(I10,6F10.4,4F10.1,2F10.2)                                      002651
00737    200 CONTINUE                                                              002651
00741    210 CONTINUE                                                              002651
00743        IF(IPLOT.EQ.0) GO TO 301                                              002651
00743  C                                                                           002651
00743  C     PLOTS                                                                 002651
00743  C                                                                           002651
00745        PRINT 211                                                             002653
00747    211 FORMAT(1H1)                                                           002657
00750        CALL MODESG(P,0)                                                      002657
00751        CALL SETSMG(P,93,0.)                                                  002663
00752        ITMAX=LAST+1                                                          002670
00753        TMMAX=TMSTOR                                                          002672
00754        DO 300 N=1,7                                                          002677
00757        XMIN=1.0E5                                                            002710
00760        YMIN=1.0E5                                                            002712
00761        ZMIN=1.0E5                                                            002713
00762        XMAX=-1.0E5                                                           002714
00763        YMAX=-1.0E5                                                           002715
00764        ZMAX=-1.0E5                                                           002716
00765        VXMIN=1.0E5                                                           002717
00766        VYMIN=1.0E5                                                           002720
00767        VZMIN=1.0E5                                                           002721
00770        TNMIN=1.0E5                                                           002722
00771        VXMAX=-1.0E5                                                          002723
00772        VYMAX=-1.0E5                                                          002724
00773        VZMAX=-1.0E5                                                          002725
00774        TNMAX=-1.0E5                                                          002726
00775        TNMIN=TMMAX-TLAST                                                     002727
00776        DO 247 K=20,ITMAX                                                     002735
01001        IF(DISP(N,1,K).LE.XMIN) XMIN=DISP(N,1,K)                              002735
01003        IF(DISP(N,2,K).LE.YMIN) YMIN=DISP(N,2,K)                              002742
01005        IF(DISP(N,3,K).LE.ZMIN) ZMIN=DISP(N,3,K)                              002750
01007        IF(DISP(N,1,K).GE.XMAX) XMAX=DISP(N,1,K)                              002756
01011        IF(DISP(N,2,K).GE.YMAX) YMAX=DISP(N,2,K)                              002764
01013        IF(DISP(N,3,K).GE.ZMAX) ZMAX=DISP(N,3,K)                              002772
01015        IF(VEL(N,1,K).LE.VXMIN) VXMIN=VEL(N,1,K)                              003000
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01017        IF(VEL(N,2,K).LE.VYMIN) VYMIN=VEL(N,2,K)          003006
01021        IF(VEL(N,3,K).LE.VZMIN) VZMIN=VEL(N,3,K)          003014
01023        IF(VEL(N,1,K).GE.VXMAX) VXMAX=VEL(N,1,K)          003022
01025        IF(VEL(N,2,K).GE.VYMAX) VYMAX=VEL(N,2,K)          003030
01027        IF(VEL(N,3,K).GE.VZMAX) VZMAX=VEL(N,3,K)          003036
01031    247 CONTINUE                                          003046
01033        IF(N.EQ.1) GO TO 245                              003046
01035        ITMAX=26                                          003051
01036        DO 220 K=1,ITMAX                                  003053
01041        C1(K)=DISP(N,1,K)                                 003061
01042        C2(K)=VEL(N,1,K)                                  003062
01043    220 CONTINUE                                          003065
01045        CALL SUBJEG(P,XMIN,VXMIN,XMAX,VXMAX)              003065
01046        CALL GRAPHG(P,0,C1,C2,6,XCHRR,6,VELX,6,TITLE)     003074
01047        CALL POINTG(P,ITMAX,C1,C2)                        003110
01050        CALL LINESG(P,ITMAX,C1,C2)                        003116
01051        CALL PAGEG(P,0,1,1)                               003124
01052        DO 230 K=1,ITMAX                                  003132
01055        C1(K)=DISP(N,2,K)                                 003141
01056        C2(K)=VEL(N,2,K)                                  003142
01057    230 CONTINUE                                          003145
01061        CALL SUBJEG(P,YMIN,VYMIN,YMAX,VYMAX)              003145
01062        CALL GRAPHG(P,0,C1,C2,6,YCHRR,6,VELY,6,TITLE)     003154
01063        CALL POINTG(P,ITMAX,C1,C2)                        003170
01064        CALL LINESG(P,ITMAX,C1,C2)                        003176
01065        CALL PAGEG(P,0,1,1)                               003204
01066        DO 240 K=1,ITMAX                                  003212
01071        C1(K)=DISP(N,3,K)                                 003221
01072        C2(K)=VEL(N,3,K)                                  003222
01073    240 CONTINUE                                          003225
01075        CALL SUBJEG(P,ZMIN,VZMIN,ZMAX,VZMAX)              003225
01076        CALL GRAPHG(P,0,C1,C2,6,ZCHRR,6,VELZ,6,TITLE)     003234
01077        CALL POINTG(P,ITMAX,C1,C2)                        003250
01100        CALL LINESG(P,ITMAX,C1,C2)                        003256
01101        CALL PAGEG(P,0,1,1)                               003264
01102    245 CONTINUE                                          003273
01103        ITMAX=LAST+1                                      003273
01104        DO 219 K=1,ITMAX                                  003301
01101        IF(DISP(N,1,K).LE.XMIN) XMIN=DISP(N,1,K)          003310
01111        IF(DISP(N,2,K).LE.YMIN) YMIN=DISP(N,2,K)          003315
01113        IF(DISP(N,3,K).LE.ZMIN) ZMIN=DISP(N,3,K)          003323
01115        IF(DISP(N,1,K).GE.XMAX) XMAX=DISP(N,1,K)          003331
01117        IF(DISP(N,2,K).GE.YMAX) YMAX=DISP(N,2,K)          003337
01121        IF(DISP(N,3,K).GE.ZMAX) ZMAX=DISP(N,3,K)          003345
01123        IF(TNS(N,1,K).LE.TNMIN) TNMIN=TNS(N,1,K)          003353
01125        IF(TNS(N,1,K).GE.TNMAX) TNMAX=TNS(N,1,K)          003361
01127    219 CONTINUE                                          003376
01131        DO 250 K=1,ITMAX                                  003376
01134        C1(K)=(TMMAX-(LAST+1.))*K                         003376
01135        C2(K)=TNS(N,1,K)                                  003403
01136    250 CONTINUE                                          003407
01140        CALL SUBJEG(P,TMMIN,TNMIN,TMMAX,TNMAX)            003407
01141        CALL GRAPHG(P,0,C1,C2,6,TIM,6,TEN,6,TITLE)        003416
01142        CALL POINTG(P,ITMAX,C1,C2)                        003432
01143        CALL LINESG(P,ITMAX,C1,C2)                        003440
01144        CALL PAGEG(P,0,1,1)                               003446
01145        IF(N.LE.1) GO TO 285                              003456
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01147   497.        DO 260 K=1,ITMAX                                            003466
01152   498.        C2(K)=DISP(N,1,K)                                           003466
01153   499.    260 CONTINUE                                                    003470
01155   500.        CALL SUBJEG(P,TMMIN,XMIN,TMMAX,XMAX)                        003470
01156   501.        CALL GRAPHG(P,0,C1,C2,6,TIM,6,XCHRR,6,TITLE)                003477
01157   502.        CALL POINTG(P,ITMAX,C1,C2)                                  003513
01160   503.        CALL LINESG(P,ITMAX,C1,C2)                                  003521
01161   504.        CALL PAGEG(P,0,1,1)                                         003527
01162   505.        DO 270 K=1,ITMAX                                            003535
01165   506.        C2(K)=DISP(N,2,K)                                           003544
01166   507.    270 CONTINUE                                                    003546
01170   508.        CALL SUBJEG(P,TMMIN,YMIN,TMMAX,YMAX)                        003546
01171   509.        CALL GRAPHG(P,0,C1,C2,6,TIM,6,YCHRR,6,TITLE)                003555
01172   510.        CALL POINTG(P,ITMAX,C1,C2)                                  003571
01173   511.        CALL LINESG(P,ITMAX,C1,C2)                                  003577
01174   512.        CALL PAGEG(P,0,1,1)                                         003605
01175   513.        DO 280 K=1,ITMAX                                            003613
01200   514.        C2(K)=DISP(N,3,K)                                           003622
01201   515.    280 CONTINUE                                                    003624
01203   516.        CALL SUBJEG(P,TMMIN,ZMIN,TMMAX,ZMAX)                        003624
01204   517.        CALL GRAPHG(P,0,C1,C2,6,TIM,6,ZCHRR,6,TITLE)                003633
01205   518.        CALL POINTG(P,ITMAX,C1,C2)                                  003647
01206   519.        CALL LINESG(P,ITMAX,C1,C2)                                  003655
01207   520.        CALL PAGEG(P,0,1,1)                                         003663
01210   521.    285 CONTINUE                                                    003673
01211   522.    300 CONTINUE                                                    003673
01213   523.        CALL EXITG(P)                                               003673
01214   524.    301 CONTINUE                                                    003677
01215   525.        TMMAX=TMSTOR                                                003677
01215   526.  C                                                                 003677
01216   527.        RETURN                                                      003700
01217   528.        END                                                         004110

     END OF COMPILATION:        NO  DIAGNOSTICS.

GPHLP
FURPUR 0026-01/11-04:57
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Appendix F

VALUES OF EACH ELEMENT OF THE TIME SERIES USED TO DESCRIBE SHIP'S VERTICAL AND LATERAL MOTIONS

This appendix lists all of the values of ω_1, $S_{h_{x_1}}$, ε_{x_1}, $S_{h_{z_1}}$, and ε_{z_1} used in equations (68), (69), and (70). Three ship headings; BETA = 90°, 135°, 180°; are used for cases 12, 13, and 14 respectively. (See chapter 4.) Thus, three sets of values will be given, one for each heading.

BETA = 90°

w_i	S_{lz_i}	ε_{z_i}	S_{lx_i}	ε_{x_i}	w_{i+1}	$S_{lz_{i+1}}$	$\varepsilon_{z_{i+1}}$	$S_{lx_{i+1}}$	$\varepsilon_{x_{i+1}}$
.4831	.0000	.0125	.0000	.0505	.4833	.0029	2.5799	.0028	2.6179
.4839	.0053	5.8041	.0051	5.8421	.4848	.0074	3.1236	.0071	3.1616
.4862	.0096	2.0287	.0092	2.0667	.4879	.0120	3.8681	.0115	3.9061
.4901	.0146	5.9648	.0140	6.0028	.4926	.0175	2.7121	.0168	2.7501
.4955	.0207	3.4010	.0198	3.4390	.4968	.0240	2.5886	.0230	2.6266
.5024	.0276	2.5731	.0264	2.6111	.5065	.0314	5.8544	.0299	5.8964
.5109	.0353	.4097	.0337	.4527	.5158	.0395	4.9092	.0377	4.9542
.5210	.0438	3.6396	.0418	3.6896	.5266	.0523	3.4171	.0495	3.4671
.5326	.0634	2.9653	.0595	3.0203	.5389	.0743	6.0026	.0694	6.0606
.5457	.0851	2.4352	.0793	2.4972	.5529	.0960	6.1445	.0893	6.2105
.5604	.1070	.2604	.0993	.3304	.5683	.1228	2.7663	.1132	2.8413
.5766	.1414	3.7703	.1296	3.8463	.5853	.1597	2.0789	.1457	2.1589
.5944	.1778	5.8207	.1617	5.9107	.6039	.1959	5.2773	.1777	5.3693
.6137	.2185	2.2562	.1967	2.3512	.6240	.2408	.5995	.2155	.7015
.6346	.2630	4.1710	.2344	4.2790	.6456	.2853	.6435	.2533	.7535
.6570	.3078	1.3917	.2718	1.5077	.6688	.3303	3.7592	.2903	3.8802
.6810	.3521	4.1661	.3078	4.2941	.6935	.3727	.3518	.3234	.4858
.7065	.3935	6.0620	.3393	6.2020	.7198	.4118	2.3342	.3522	2.4792
.7335	.4297	4.3366	.3646	4.4966	.7476	.4446	.8059	.3740	.9809
.7621	.4589	4.5459	.3826	4.7259	.7770	.4713	5.0016	.3890	5.1876
.7923	.4820	4.6990	.3936	4.8910	.8079	.4911	3.5674	.3964	3.7674
.8239	.4965	3.4918	.3974	3.7068	.8404	.5042	2.2141	.3967	2.4441
.8572	.5079	3.0519	.3944	3.2919	.8744	.5110	2.9042	.3908	3.1592
.8920	.5129	2.7346	.3858	3.0046	.9099	.5138	4.4963	.3797	4.7813
.9283	.5138	1.6860	.3726	1.9860	.9470	.5124	5.3313	.3645	5.6563

BETA = 135°

W_i	$S_{\ell z i}$	E_{zi}	$S_{\ell x i}$	E_{xi}	W_{i+1}	$S_{\ell z i+1}$	$E_{z i+1}$	$S_{\ell x i+1}$	$E_{x i+1}$
.4831	.0000	.0125	.0000	.4125	.4833	.0032	2.5799	.0021	2.9799
.4839	.0059	5.8041	.0038	6.2041	.4648	.0083	3.1236	.0054	3.5236
.4862	.0109	2.0287	.0070	2.4287	.4879	.0137	3.8681	.0088	4.2681
.4901	.0168	5.9648	.0107	6.3648	.4926	.0202	2.7121	.0128	3.1121
.4955	.0238	3.4010	.0151	3.8030	.4988	.0277	2.5886	.0176	2.9916
.5024	.0319	2.5731	.0202	2.9781	.5065	.0363	5.8544	.0229	6.2644
.5109	.0409	.4097	.0258	.8247	.5158	.0458	4.9092	.0288	5.3292
.5210	.0508	3.6396	.0320	4.0696	.5266	.0613	3.4171	.0380	3.8571
.5326	.0752	2.9653	.0459	3.4153	.5389	.0888	6.0026	.0536	6.4626
.5457	.1022	2.4352	.0613	2.9052	.5529	.1157	6.1445	.0691	6.6245
.5604	.1293	.2604	.0769	.7504	.5683	.1503	2.7663	.0881	3.2663
.5766	.1756	3.7703	.1014	4.2803	.5853	.2002	2.0789	.1144	2.5989
.5944	.2244	5.8207	.1274	6.3607	.6039	.2486	5.2773	.1403	5.8373
.6137	.2827	2.2562	.1566	2.8262	.6240	.3160	.5995	.1728	1.1995
.6346	.3490	4.1710	.1888	4.7810	.6456	.3823	.6435	.2051	1.2735
.6570	.4198	1.3917	.2222	2.0317	.6688	.4570	3.7592	.2393	4.4342
.6810	.4948	4.1661	.2557	4.8561	.6935	.5335	.3518	.2710	1.0668
.7065	.5721	6.0620	.2864	6.7920	.7198	.6103	2.3342	.3000	3.1042
.7335	.6483	4.3366	.3132	5.1366	.7476	.6847	.8059	.3247	1.6459
.7621	.7205	4.5459	.3354	5.4059	.7770	.7548	5.0016	.3441	5.9016
.7923	.7875	4.6990	.3513	5.6490	.8079	.8185	3.5674	.3568	4.5474
.8239	.8475	3.4918	.3608	4.5168	.8404	.8749	2.2141	.3633	3.2841
.8572	.9012	3.0519	.3646	4.1719	.8744	.9237	2.9042	.3639	4.0792
.8920	.9433	2.7346	.3615	3.9646	.9099	.9608	4.4963	.3578	5.7663
.9283	.9762	1.6860	.3528	3.0060	.9470	.9895	5.3313	.3462	6.7213

BETA = 135°

W_i	$S_{\ell z i}$	E_{zi}	$S_{\ell x i}$	E_{xi}	W_{i+1}	$S_{\ell z i+1}$	$E_{z i+1}$	$S_{\ell x i+1}$	$E_{x i+1}$
.9661	1.0028	4.3333	.3389	5.7733	.9857	1.0075	2.1606	.3301	3.6606
1.0056	1.0118	2.4800	.3203	4.0400	1.0259	1.0107	5.1920	.3096	6.8020
1.0465	1.0088	1.5916	.2978	3.2616	1.0676	1.0041	1.8399	.2855	3.5799
1.0890	.9977	3.6154	.2719	5.4154	1.1109	.9812	.0295	.2588	1.8695
1.1331	.9631	5.8990	.2445	7.7690	1.1557	.9431	2.4066	.2298	4.3086
1.1787	.9164	4.9127	.2150	6.8427	1.2021	.8814	.9350	.2003	2.8950
1.2258	.8399	.8681	.1871	2.7681	1.2500	.7928	.2159	.1732	2.0739
1.2745	.7397	3.8145	.1574	4.9845	1.2995	.6820	2.9536	.1425	4.7136
1.3248	.6190	3.7743	.1303	5.3843	1.3505	.5451	.2900	.1162	1.7530
1.3765	.4692	4.6000	.1019	5.7300	1.4030	.4137	4.6010	.0921	5.7610
1.4299	.3462	1.1285	.0805	2.0935	1.4571	.2748	3.5946	.0688	4.3946
1.4848	.2293	2.3799	.0616	2.9799	1.5128	.1692	.6888	.0530	1.1488
1.5412	.1111	3.4924	.0455	3.8424	1.5700	.0925	6.0899	.0418	6.3199
1.5991	.0678	.0560	.0374	.1870	1.6287	.0541	4.5323	.0348	4.6523
1.6586	.0517	2.6680	.0333	2.7730	1.6890	.0491	3.9707	.0317	4.0627
1.7197	.0463	1.6688	.0303	1.7548	1.7508	.0432	5.2955	.0287	5.3755
1.7823	.0396	.1910	.0268	.2660	1.8142	.0349	5.4516	.0245	5.5166
1.8465	.0292	3.3601	.0219	3.4051	1.8791	.0246	5.6802	.0196	5.7022
1.9122	.0194	.0065	.0172	.0185	1.9456	.0141	1.6000	.0147	1.5900
1.9794	.0107	5.4180	.0127	5.3780	2.0136	.0052	4.3815	.0101	4.3415
2.0482	.0050	1.4546	.0087	1.4146	2.0832	.0047	5.0626	.0071	5.0226
2.1185	.0046	.9919	.0067	.9619	2.1543	.0046	2.3343	.0070	2.3043
2.1904	.0047	.8976	.0068	.8776	2.2269	.0047	5.5249	.0061	5.5099
2.2638	.0046	4.2004	.0054	4.2114	2.3011	.0042	4.6728	.0050	4.6628
2.3388	.0038	2.5547	.0047	2.5447	2.3768	.0034	3.2059	.0043	3.1959
2.4153	.0028	2.9858	.0039	2.9758					

BETA = 180°

W_i	Sl_{zi}	E_{zi}	W_{i+1}	Sl_{zi+1}	E_{zi+1}
.4831	.0000	.0125	.4833	.0035	2.5799
.4839	.0064	5.8041	.4848	.0091	3.1236
.4862	.0119	2.0287	.4879	.0151	3.8661
.4901	.0185	5.9648	.4926	.0223	2.7121
.4955	.0263	3.4010	.4988	.0307	2.5886
.5024	.0353	2.5731	.5065	.0402	5.8544
.5109	.0453	.4097	.5158	.0507	4.9092
.5210	.0563	3.6396	.5266	.0683	3.4171
.5326	.0843	2.9653	.5389	.0998	6.0026
.5457	.1152	2.4352	.5529	.1305	6.1445
.5604	.1460	.2604	.5683	.1704	2.7663
.5766	.1998	3.7703	.5853	.2284	2.0769
.5944	.2565	5.8207	.6039	.2845	5.2773
.6137	.3247	2.2562	.6240	.3639	.5995
.6346	.4025	4.1710	.6456	.4418	.6435
.6570	.4868	1.3917	.6688	.5314	3.7592
.6810	.5760	4.1661	.6935	.6208	.3518
.7065	.6656	6.0620	.7198	.7089	2.3342
.7335	.7520	4.3366	.7476	.7948	.8059
.7621	.8354	4.5459	.7770	.8710	5.0016
.7923	.9031	4.6990	.8079	.9316	3.5674
.8239	.9564	3.4918	.8404	.9786	2.2141
.8572	1.0008	3.0519	.8744	1.0125	2.9042
.8920	1.0181	2.7346	.9099	1.0192	4.4963
.9283	1.0156	1.6860	.9470	1.0070	5.3313

BETA = 180°

W_i	$S_{\ell z i}$	ε_{zi}	W_{i+1}	$S_{\ell z i+1}$	$\varepsilon_{z i+1}$
.9661	.9971	4.3333	.9857	.9747	2.1606
1.0056	.9497	2.4800	1.0259	.9165	5.1920
1.0465	.8792	1.5916	1.0676	.8350	1.8399
1.0890	.7855	3.6154	1.1109	.7335	.0295
1.1331	.6736	5.8990	1.1557	.6025	2.4086
1.1787	.5322	4.9127	1.2021	.4652	.9350
1.2258	.4064	.8681	1.2500	.3428	.2159
1.2745	.2595	3.8145	1.2995	.1865	2.9536
1.3248	.1606	3.7743	1.3505	.1278	.2900
1.3765	.0962	4.6000	1.4030	.0926	4.6010
1.4299	.0887	1.1285	1.4571	.0876	3.5946
1.4848	.0938	2.3799	1.5128	.0999	.6888
1.5412	.0983	3.4924	1.5700	.0839	6.0899
1.5991	.0655	.0560	1.6287	.0507	4.5323
1.6586	.0365	2.6680	1.6890	.0186	3.9707
1.7197	.0149	1.6688	1.7508	.0127	5.2955
1.7823	.0107	.1910	1.8142	.0100	5.4516
1.8465	.0093	3.3601	1.8791	.0085	5.6802
1.9122	.0075	.0065	1.9456	.0064	1.6000
1.9794	.0052	5.4180	2.0136	.0037	4.3815
2.0482	.0028	1.4546	2.0832	.0013	5.0626
2.1185	.0021	.9919	2.1543	.0033	2.3343
2.1904	.0038	.8976	2.2269	.0038	5.5249
2.2638	.0038	4.2004	2.3011	.0039	4.6728
2.3388	.0038	2.5547	2.3768	.0034	3.2059
2.4153	.0028	2.9658			

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